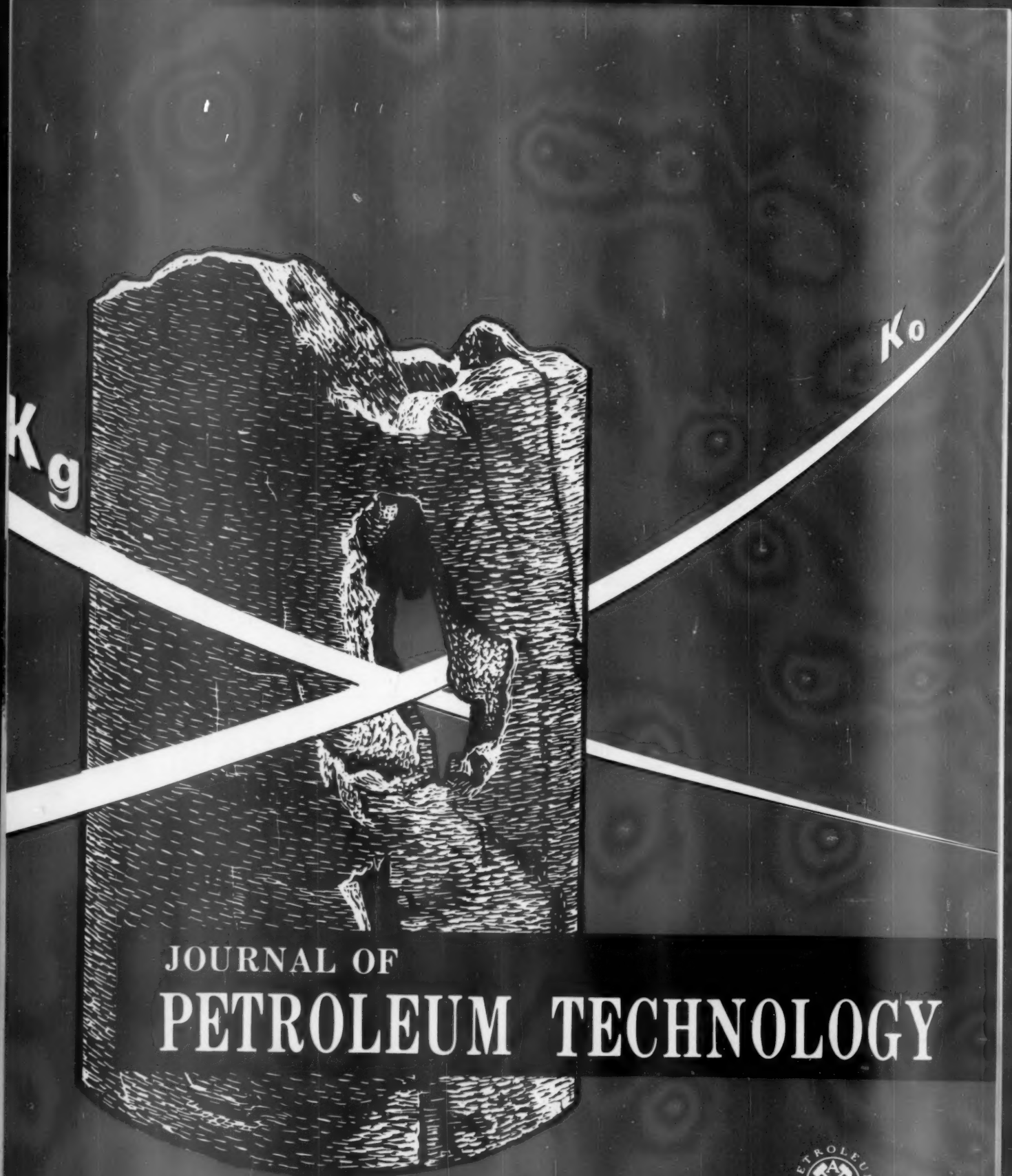


# JOURNAL OF PETROLEUM TECHNOLOGY

AUGUST 1955

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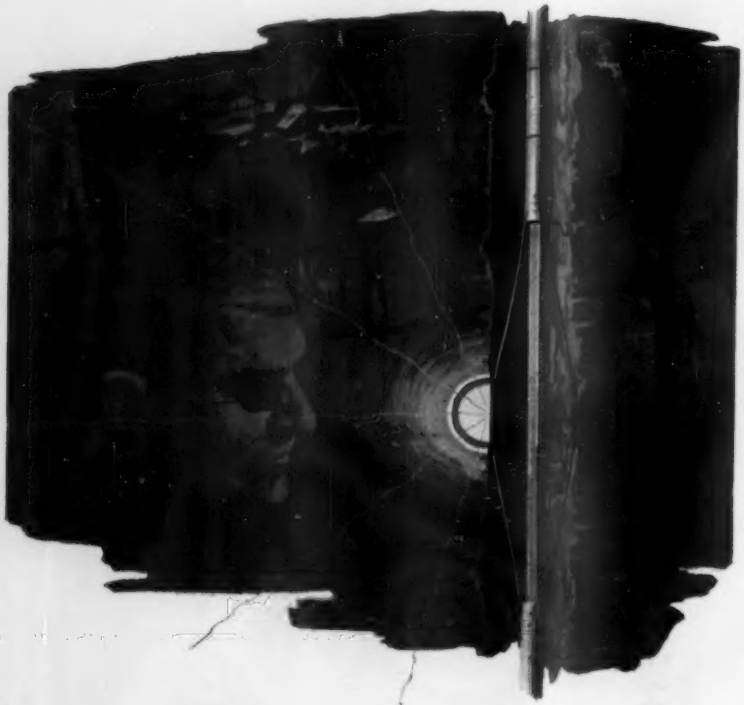

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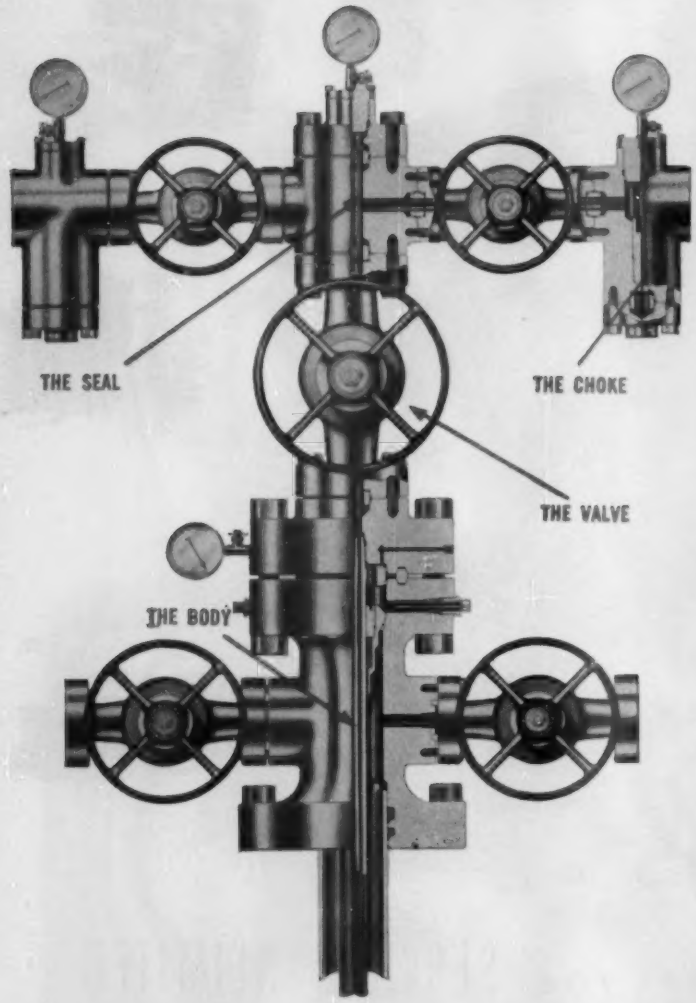


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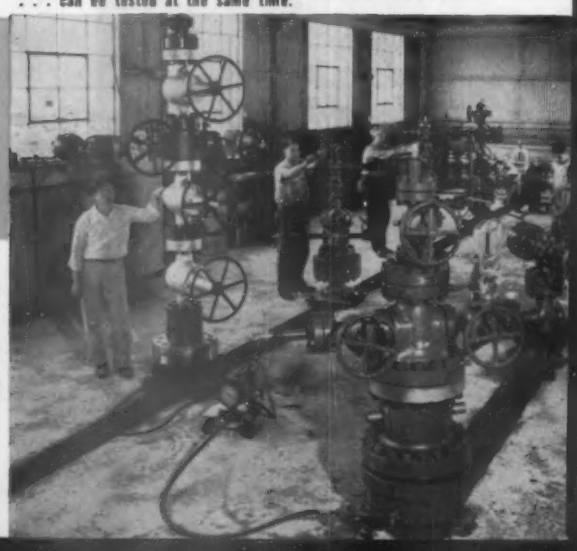

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*On the Cover: The curve showing relative gas and oil permeability vs total liquid saturation is taken from a paper starting on page 128 of this issue. The title of this paper, to which a discussion is offered by Thomas S. Hutchinson of The Atlantic Refining Co., is "Analysis of Reservoir Performance $K_g/K_o$ Curves and a Laboratory $K_g/K_o$ Curve Measured on a Core Sample."*

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>
> (*Effectiveness of Gun Perforating, Journal of Petroleum Technology, January, 1954.*)

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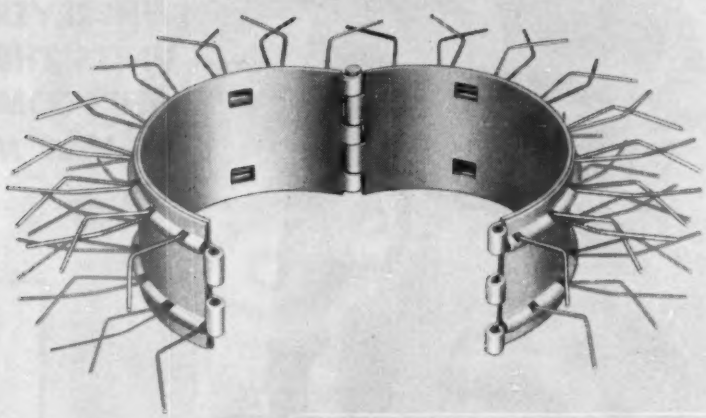

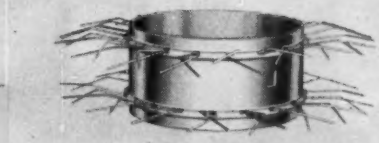

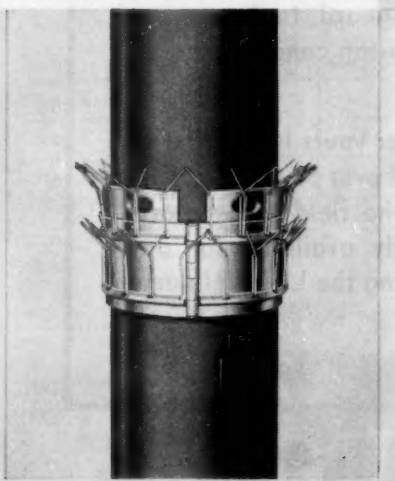

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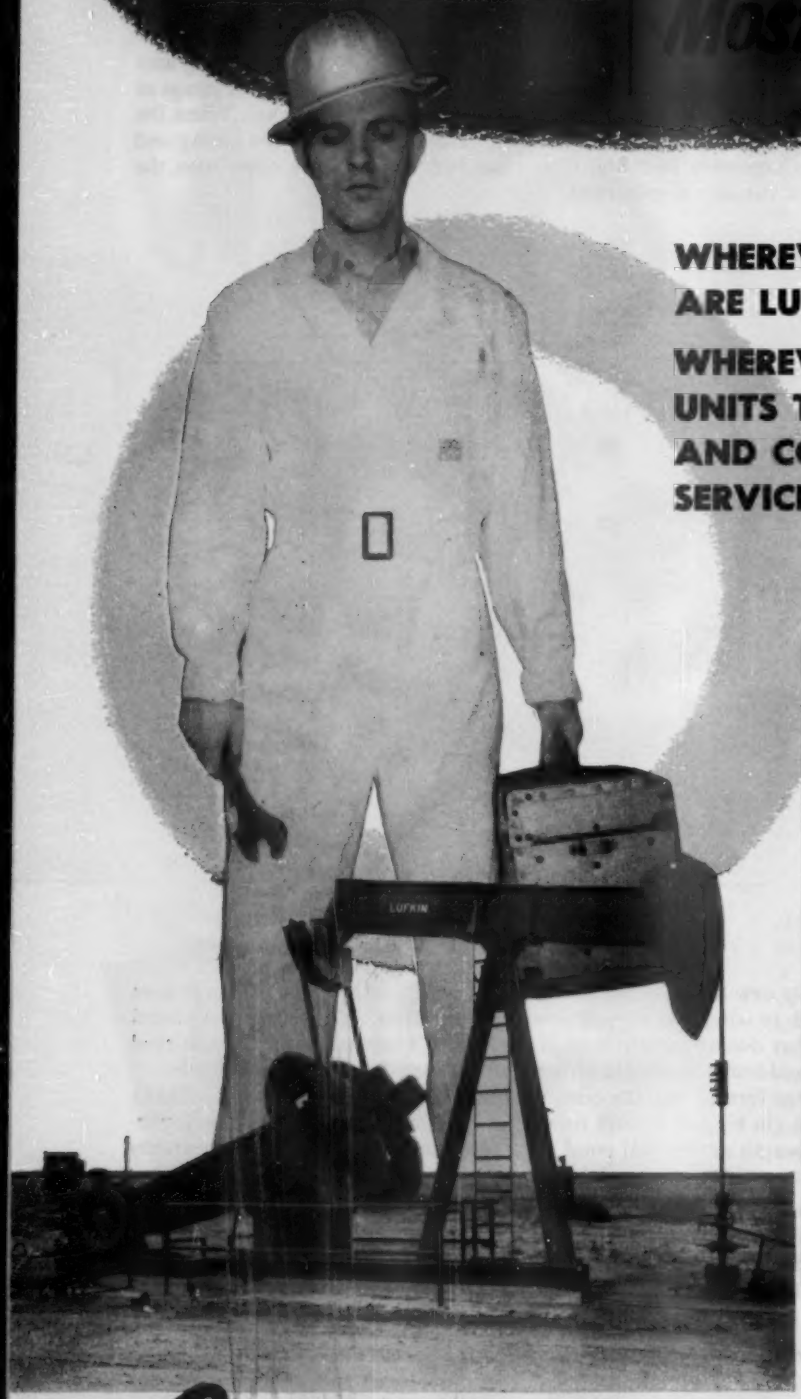

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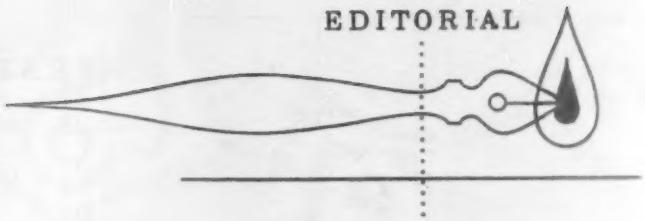
*This is the first of a series of editorials to be written on "What AIME Means to Me" by long-standing members of the Petroleum Branch, AIME.*

EDITORIAL



# WHAT AIME MEANS to ME

W. H. GEIS
*MEMBER AIME*

*PETROLEUM CONSULTANT*
*LOS ANGELES, CALIF.*

I find it quite difficult adequately to express "what AIME means to me" although I could with ease, and with many suggestions from local members, express "what I think of AIME." However, I find the subjects are not synonymous.

Under the latter title all my restrained critical inhibitions could be released, and using the negative to a doubtful advantage, I might point out everything the Institute is not. However, a little reflection brings the sobering thought that much of what the AIME means to me may result not only from what it is but from what it is not.

Certainly it is not an organization that can be taken lightly as having only a slight or passing impact on its members. The longer my membership endures, the more personal is the relationship until the Institute seems to acquire characteristics of an ethical professional and technical Alter Ego.

Some authority attaches to my observation for I was first a Student Associate about 1914. When I reflect on what the AIME has meant, and still means to me, the tendency is to become philosophical which may be taken as a sign of asymptotic mental maturity. However, in the days of my student innocence AIME stood as a symbol. It marked professional integrity, for the dean and professors had cards announcing their membership to the world and these men were engineers. There appeared to be some doubt in my mind, and in theirs as well, that I could ever merit the same status. But when accepted as a Student Associate of AIME, I gained some assurance. Surely the Institute would not open its doors to one without possibilities. Moreover, I read, either by assignment or otherwise, many of the technical papers and thus came to know the authors, at least in the abstract. Now the situation has reversed, I know the authors but only read the abstracts.

Again in my guileless student days I considered all professors as necessarily profound and erudite. My opinion of AIME was considerably advanced when I discovered that much of that profundity came from the *Transactions*. If there is such a thing as academic freedom, it is well revealed in the said *Transactions* and nowhere therein can I find a Fifth Amendment hedge. AIME is not only an Institute of Mining, Metallurgical, and Petroleum Engineers but above all it is American. Little wonder then that I am proud of my membership. It means a very great deal to me.

So there was a considerable impact from AIME, not all recorded here, in my early experience. But as engineering adolescence progressed, the Institute came to mean more to me but in quite a different way. As a practicing, if not practical, engineer, problems were always arising which were quite new to me but not to AIME. Identical situations were described and solutions recorded in the red-bound tomes. It is perhaps understandably excusable if my solutions bordered on engineering plagiarism. After all AIME had become, and still is, a technical godfather, a silent advisor, a confidant — asking little in return for what it gives. My contribution has been largely financial, but I now realize that in the exchange I came out the richer by far.

So as I consider "what AIME means to me" I begin to understand that with time some organizations become personified. Thus it is with your political party, your church, your fraternity and lodge, the university, the club, etc. Each has a definite personality, position and influence in your life. It will be difficult to visualize progress without these relationships. And so it is with the Institute. For a long time it has just been a part of my professional life. Too many, quite like myself, have become accustomed simply to accept AIME as something apart. However, if in the inner conscience you ask yourself, as I hope you will, just "what does AIME mean to me" you will in honesty find it has played a far greater role in your development than you realize.

Just one additional thought. I find myself fortunate in having a legion of constructive friends all over the world. My first contact with many of these came through some Institute activity. Hence, along with the technical-professional aspects of AIME, there are social-professional connotations. It all might be concluded by saying that what my profession and friends mean to me, so also does AIME mean. ★★★

FEATURE ARTICLE

# LOG INTERPRETATION PROBLEM in LOW RESISTIVITY SANDS

HAROLD A. BLUM*
*MEMBER AIME*
JOHN L. MARTIN
*JUNIOR MEMBER AIME*

*THE ATLANTIC REFINING CO.*
*DALLAS, TEX.*

## Abstract

*All recent investigations have attributed low electric log resistivities in producing formations to a conductive ion layer associated with clay material present in the sands. In this study another mechanism is proposed. It is believed that connate water saturation variations (which may or may not be associated with shale contact) also contribute to low resistivities.*

*In addition to the mechanistic studies, evaluation of various recently proposed interpretation methods have been made. Of these, the Poupon, Loy, and Tixier[3] and de Witte[2] methods seem best.*

## Statement of Problem

Low resistivity sands are often encountered which turn out to be commercial hydrocarbon zones but appear from electric log data to be water bearing. Adequate methods of recognizing these cases are needed. Industry-wide interest in this problem is evidenced by the number of papers published in recent years.[1-9]

It seemed that several zones in the Mustang Island field (Nueces County, Tex.) were affected by the shaly sand problem. This was evidenced by: (1) low hydrocarbon saturation calculations from logs and measured formation factor data in producing zones, (2) changes in apparent measured formation factors with changes in water resistivity, and (3) core descriptions which indicated the presence of shaly "streaks" or "spots." A section of a typical log is shown in Fig. 1. All sands on this log are hydrocarbon zones.

## Scope of Investigation

The Mustang Island field, Nueces County, Tex.,[10] has been chosen for the study of the shaly sand problem because the oil-water contacts are well established for most of the sands and some core data were available for study.

This problem has been approached by both empirical and experimental methods. The empirical portion of this study is a comparison of calculated hydrocarbon saturations from logs by various methods with expected or known production (oil, gas, or water).

The experimental phases of the investigation involve work with Mustang Island cores to estimate the effect of the conductive ion layer on hydrocarbon saturation calculations. Both de Witte[2] and Patnode and Wyllie[3] approaches have been considered in this work. In addition, the possibility that connate water saturation variations within shaly sand bodies also cause low resistivities has been investigated.

## Experimental Studies

### Introduction

Much of the published work on shaly sands has been concerned with the mechanism by which the presence of shaly material affects both resistivity curves and the *SP*.

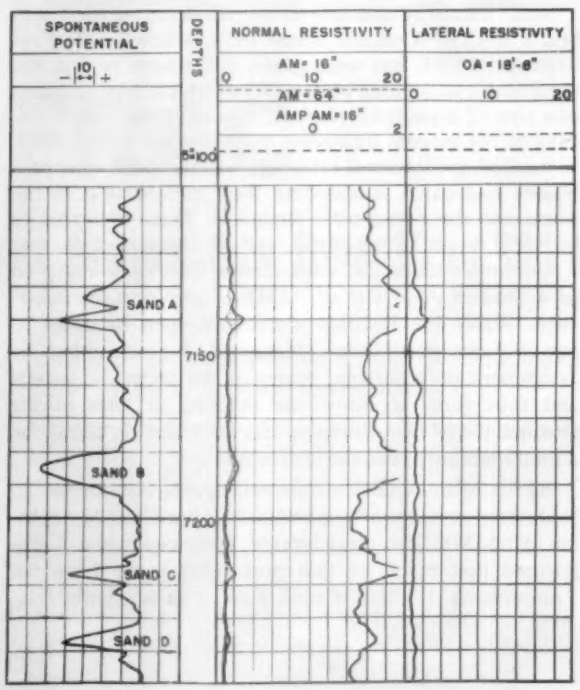



**Fig. 1 — Section of typical log in Mustang Island field, Nueces County, Tex. Sands A, B, C, D are all hydrocarbon zones.**

[1]References given at end of paper.
Manuscript received in Petroleum Branch office on March 31, 1955.
*Harold A. Blum is now associate professor of petroleum engineering at Texas Technological College.

It has been pointed out by the various authors[4, 6, 9] that the negative charges on the clay lattice are coexistent with a balancing concentration of positive ions in the solution adjacent to the clay surfaces. The impression left by these investigators is that a knowledge of the relationship between the conductance of this clay-adjacent solution portion of a shaly sand system to the total conductance will solve the shaly sand problem.

There is no question about the importance of this approach and its contribution to date, but there remains a serious doubt that this approach is the whole answer to the shaly sand problem. One possibility considered here is that connate water saturation variations exist in shaly sands and are partially responsible for the low resistivity log problem.

### Ionic Layer Effects on Connate Water Saturation Calculations in Sand B

When it became evident that there was a low resistivity problem in Mustang Island field, a study was undertaken to determine the conductive layer effects.

Plugs were cut from wire line cores, dried, and placed in an extractor where a carbon tetrachloride extraction was carried out. The plugs were then saturated with 0.048 ohm-m (75° F) brine and placed in a resistivity cell where the resistivities were determined. The plugs were then flushed with 0.086 ohm-m brine until the resistivity of the effluent brine equaled 0.086 ohm-m. Plug resistivities were measured again. This process was repeated for 0.36 and 1.05 ohm-m brines.

Generally 50 to 100 pore volumes were flushed through the core for each change of water resistivity.

The effect of temperature on resistivity of the plugs was also measured in a few cases.

The apparent formation factors $(R_o/R_w)$* decreased with increase in water resistivity as shown in Fig. 2. This, of course, is typical of the behavior of shaly sand core material.[2] The data are represented by the two limiting curves shown.

In order to determine the effect of the clay material on saturation calculations, the data in Fig. 2 were applied to equations suggested by Patnode and Wyllie[2] and de Witte[3] for this purpose.

The Patnode and Wyllie equations (assuming the parallel resistor analogy) are:
$1/R_o = 1/R_{es} + 1/FR_W$ (for a water saturated system), $R_{es}$ is the ionic layer resistivity $R_o = F_s \cdot R_w$; $F = F_s$ as $R_w \rightarrow 0$ . . . . . Equation 1

$$\frac{1}{R_T} = \frac{1}{R_{es}} + \frac{S_w^n}{FR_W}$$ for cases where sand is not 100 per cent water saturated . . . . . Equation 2

The term, $n$, is the saturation exponent in the Archie equation.[11]

The de Witte[3] equations are based on the assumption that the conductivity of a clay-brine solution can be represented in the same way as a mixture of electrolytes.

For a water saturated system the equation is as follows: $$\frac{1}{R_o} = \frac{1 - X_w}{R_c} + \frac{X_w}{FR_w}$$ . . . . . Equation 3

$X_w$ is the volume fraction of the conductive system (clay-brine) which is brine, $F$ is the same value as used in the Patnode and Wyllie method, i.e. $F_s \rightarrow F$ as $R_w \rightarrow 0$, and $R_c$ is the ionic layer resistivity.

*A complete list of definitions of all terms is given at the end of the paper.

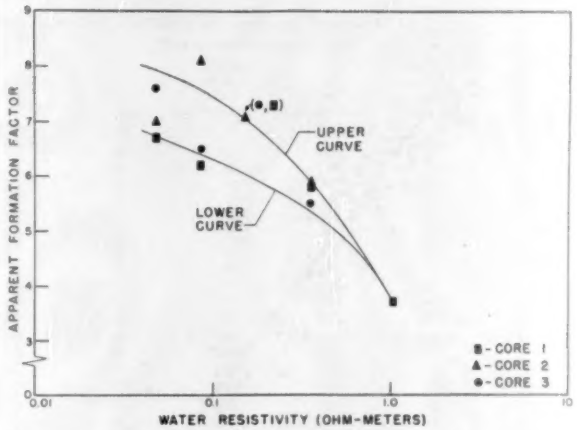



**Fig. 2 — Apparent formation factor vs water resistivity Sand B, Mustang Island field, Nueces County, Tex.**

To calculate the connate water saturation $(S_w)$ for the sand which is not 100 per cent water saturated, de Witte[3] derived the following equation:

$$S_w^2 + \left[\frac{\frac{R_c}{F} + R_w}{N}\right] S_w + \frac{\left[\frac{R_c}{F}\right]\left[R_w\right]\left[R_t\right] - \left[N + \frac{R_c}{F}\right]\left[N + R_w\right] R_o}{R_t N^2} = 0$$

. . . . . Equation 4

where $N = \left[\frac{X_w}{1 - X_w}\right]\left[\frac{R_c}{F}\right]$

Connate water saturation calculations were attempted for $R_{es}$ and $R_c$ values obtained from the upper and lower curves of Fig. 2. In one set of calculations no attempt was made to correct $R_{es}$ or $R_c$ to formation temperature. Another set assumed the sodium chloride solution temperature corrections for resistivity applied. Experiments indicate that the correction is much less than would be expected for sodium chloride solutions but not enough quantitative data are available to apply accurate corrections.

Table 1 summarizes the connate water saturation calculations made for the various conditions. In each case the condition was chosen to result in the greatest ionic layer effect. For the Patnode and Wyllie approach the lowest calculated $R_{es}$ was used. The lowest $X_w$ and $R_c$ were used in applying the de Witte method.

Where no temperature corrections were made for $R_t$ and $R_{es}$ the ionic layer effects are small. For the less reliable case where temperature corrections are assumed, the ionic layer effects are significant.

TABLE 1 — CALCULATED WATER SATURATIONS UNDER VARYING CONDITIONS

| | $S_w$ | |
|---|---|---|
| | No Temperature Correction For $R_{es}$ or $R_c$ | Temperature Correction* To Formation Temperature For $R_{es}$ or $R_c$ |
| Patnode and Wyllie[2] | | |
| Upper Curve (Fig. 2) | 0.56 ($R_{es}$ = 6.7) | 0.50 |
| Lower Curve (Fig. 2) | 0.50 ($R_{es}$ = 6.2) | 0.44 |
| de Witte[3] | | |
| Upper Curve (Fig. 2) | 0.60 | 0.45 |
| Lower Curve (Fig. 2) | 0.55 | 0.40 |
| Archie (No Ionic Layer corrections) n = 1.8 | | |
| Upper Curve (F = 8.3) | 0.61 | |
| Lower Curve (F = 7.0) | 0.56 | |

*Sodium chloride solution corrections

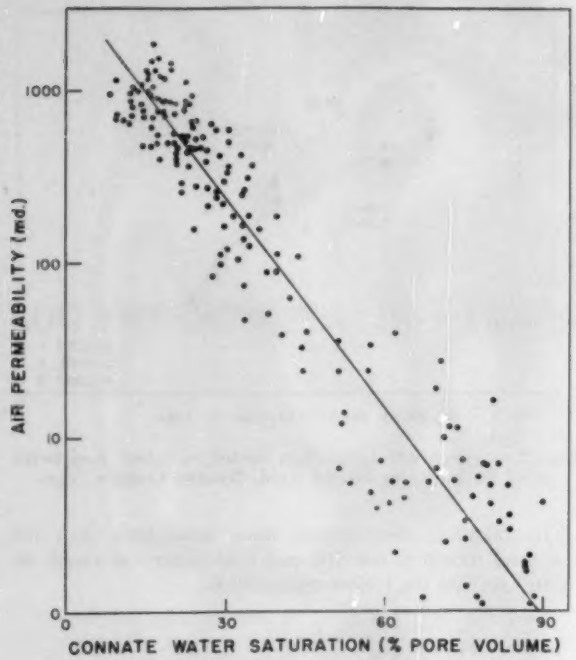



**Fig. 3 — Air permeability vs connate water saturation for several sands in the Mustang Island field, Nueces County, Tex.**

### Relationship Between Permeability and Connate Water Saturation and Its Importance to the Shaly Sand Problem

In a study of the Frio Sand, a relationship between laboratory connate water saturations and air permeability has been observed. The correlation is shown in Fig. 3.

This relationship could be important to the solution of the shaly sand problem because many core data reports from the Mustang Island field indicate cases where very marked permeability changes occur within a sand zone.

Frequently it will be observed that vertical permeabilities are much less than horizontal values. Furthermore, descriptions of sands by geologists and engineers are replete with indications that the sands are "shaly."

In other words, the presence of these shaly sand heterogeneities indicate high connate water streaks or spots which could be as responsible for low resistivities as the conductive paths provided by the clay lattice or shale laminations. Assuming negligible conductive shale effects, the presence of high connate water sections within a sand can be represented by the following equation:

$$\frac{1}{R_{TA}} = \frac{W_1}{R_{T_1}} + \frac{W_2}{R_{T_2}} + \frac{W_3}{R_{T_3}} \cdots \frac{W_m}{R_{T_m}} \quad \text{Equation 5}$$

where $R_T$ apparent ($R_{TA}$) is the average true resistivity for the section (not necessarily the apparent log resistivity), $R_{T_m}$ is the true resistivity of a relatively homogeneous section within the zone of interest, and $W_m$ represents the volume fraction of the homogeneous portion of the system represented by $R_{T_m}$ where

$W_1 + W_2 + W_3 \ldots + W_m = 1$

$$R_{T_m} = \frac{R_{om}}{S_m^n} \text{(Archie equation)} \quad \text{Equation 6}$$

or $$\frac{1}{R_{TA}} = \frac{W_1 S_1^n}{R_{o_1}} + \frac{W_2 S_2^n}{R_{o_2}} + \ldots \frac{W_m S_m^n}{R_{o_m}} \quad \text{Equation 7}$$

If $R_o$ is a constant in this system (formation factors have been frequently noted to be relatively constant even though permeability variations were large), then

$$\frac{R_o}{R_{TA}} = W_1 S_1^n + W_2 S_2^n + \ldots W_m S_m^n$$

**EXAMPLE 1: (Synthetic)**

Assume a system with the following makeup

| | |
|---|---|
| $S_1 = .10$ | $W_1 = .4$ |
| $S_2 = .20$ | $W_2 = .3$ |
| $S_3 = .60$ | $W_3 = .2$ |
| $S_4 = .75$ | $W_4 = .1$ |

The connate water saturation for the whole system is,

$S_w = 0.4\ (0.1) + 0.3\ (0.2) + 0.2\ (0.6) + 0.1\ (0.75) = 0.295.$

Applying this $S_w$ to the Archie equation where

$R_o = 0.35$ $n = 1.8$, $R_T$ would be $\frac{0.35}{0.295^{1.8}} = 3.2$ ohm-m.

Using the suggested equations would result in an $R_{TA} = 2.2$ ohm-m

$\left(\frac{1}{R_{TA}} = \frac{1}{.35}\ (.0064 + .0165 + .0800 + .0595) = \frac{.1624}{.35}\right.$

$\left.\text{or } R_{TA} = 2.2 \text{ ohm-m.}\right)$

**EXAMPLE 2:**

The following data were available for a Sand D oil zone

| $k_{air}$ (md) | Connate Water Saturation (Fig. 3) | Porosity ($\phi$) | Formation Factor $F = \frac{1}{\phi^{1.8}}$ |
|---|---|---|---|
| 870 | 16.5 | 34.6 | 6.9 |
| 32 | 51.8 | 25.5 | 12.0 |
| 7 | 68 | 22.6 | 15.0 |
| 224 | 31 | 27.5 | 10.9 |
| 6 | 70 | 24.1 | 13.1 |
| 21 | 56 | 25.6 | 12.0 |
| 204 | 32 | 30.4 | 9.0 |
| | | | 78.9 |

$F_{av} = 11.3$

$R_T = 1.4$ ohm-m (log) $R_o = 11.3 \times .05 = 0.56$ ohm-m.

Assuming equal weight or $W_1 = W_2 = W_3 \ldots W_7$ the average connate water saturation is 46 per cent compared with a log calculated value of 60 per cent.

It can be readily seen from Example 1 that a lower $R_T$ would be expected from the log than the uncorrected Archie equation would predict. Example 2 shows comparison of actual with calculated $S_w$. The major difference between this approach and the laminar shale mechanism proposed by Doll[14] is that the cause of low resistivity proposed here is due to connate water saturation variations in shaly sand rather than to the conductivity of shale streaks alone.

## Evaluation of Recently Proposed Interpretation Methods

From 1953 to this writing five methods for log interpretation in shaly sands have been proposed[4,5,6,7,9]. The evaluation carried out in this investigation consisted simply of calculating the hydrocarbon saturation with each method and comparing the results with known or expected production (oil, gas, or water). The hydrocarbon saturations obtained from the Archie equation[11] are also included in this study.

The validity of the various proposed mechanisms and derivations which led to the statement of the various methods were not considered in this investigation. A summary describing how to use each method is found in the Appendix.

The above methods were used to calculate hydrocarbon saturations for Sands A, B, C, and D in six wells of the field where necessary data were available.

Results which are summarized in Table 2 indicate that *where hydrocarbon zones are known to exist* the de Witte (Equation 29 of Reference 9) and Poupon et al[5] methods seem best.

The basis for comparison is the discrimination of each method between hydrocarbon and water zones. Table 3 compares the methods on this basis.

TABLE 2 — SUMMARY OF DATA* FOR HYDROCARBON SATURATION CALCULATIONS IN MUSTANG ISLAND FIELD

| Well | Sand | SP (mv) | $R_{xo}$ (Ωm) | $R_t$ (Ωm) | F | Hydrocarbon Saturation (Per Cent) Archie[10] | Poupon et al.[5] | Wyllie et al.[4] and Perkins et al[6] | de Witte[9] Simplified Eq. 29 | White**[7] and de Witte Simplified Eq. 28[9] | Oil, Gas or Water (O, G, W) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A | 70 | 2.4 | 0.5 | 6.0 | 23 | 30 | 35 | 60X | 37 | W |
| | B | 60 | 2.3 | 0.3 | 6.0 | 0 | 0 | 0 | 9 | 4 | W |
| | C | 60 | 2.0 | 0.3 | 5.0 | 0 | 0 | 0 | 21 | 11 | W |
| | D | 30 | 2.2 | 0.6 | 6.0 | 29 | 0 | 0 | 0 | 0 | W |
| 2 | A | 45 | 3.0 | 2.9 | <5 | >70 | 75 | 52 | 87 | 63 | O |
| | B | 50 | 9.0 | 0.4 | 16 | 0 | 0 | 0 | 0 | 0 | W |
| | C | 55 | 1.9 | 0.4 | 3.3 | 37 | 20 | 15 | 32 | 17 | W |
| | D | 25 | 1.7 | 0.5 | 3.3 | 47 | 0 | 0 | 0 | 0 | W |
| 3 | A | 40 | 3.3 | 13 | 7.3 | 83 | >90 | 75 | 95 | 80 | O |
| | B | 40 | 2.2 | 2.0 | 4.8 | 65 | 71 | 47X | 79 | 59 | O |
| | C | 40 | 2.2 | 1.2 | 4.8 | 55 | 55 | 32X | 64 | 47X | O |
| 4 | A | 40 | 2.8 | 7.5 | 5 | 82 | 90 | 70 | 93 | 76 | G |
| | B | 45 | 2.8 | 1.1 | 5 | 52 | 50 | 26X | 58 | 42X | O |
| | C | 45 | 2.2 | 1.4 | 4.2 | 61 | 63 | 42X | 75 | 55 | G |
| | D | 55 | 2.9 | 0.7 | 5.3 | 39X | 35X | 20X | 53 | 39X | G |
| 5 | A | 50 | 3.7 | 3.5 | 7.0 | 68 | 74 | 56 | 86 | 66 | O |
| | B | 50 | 2.0 | 1.0 | 3.8 | 56 | 57 | 40X | 73 | 53 | O |
| | C | 50 | 2.0 | 1.2 | 3.8 | 60 | 64 | 45X | 77 | 52 | O |
| | D | 15 | 2.0 | 1.0 | 3.8 | 56 | 0X | 0X | 6X | 13X | O |
| 6 | A | 50 | 4.3 | 4.6 | 6.2 | 74 | 74 | 60 | 87 | 68 | O |
| | B | 55 | 2.5 | 1.0 | 3.6 | 58 | 55 | 39X | 71 | 52 | O |
| | C | 50 | 3.1 | 1.0 | 4.5 | 53 | 38X | 28X | 58 | 42X | O |
| | D | 35 | 2.0 | 1.0 | 2.9 | 62 | 52 | 23X | 53 | 39X | O |

* $R_w$ at 155° F = 0.05 Ωm, $S_{xo}$ = 0.80 (assumed) for hydrocarbon zones.

X Disagreement between known or expected production and calculated hydrocarbon saturation (50 per cent critical saturation is criterion).

** Only difference between White Equation and de Witte Equation 28 is the exponent of the $S_{xo}/S_w$ term. de Witte uses 2 whereas White uses 2.15. de Witte uses this equation for relatively clean sands.

TABLE 3 — DISCRIMINATION OF HYDROCARBON ZONES FROM WATER ZONES BY VARIOUS INTERPRETATION METHODS

| | Archie[10] | Poupon et al.[5] ($S_{xo}$ = 80) | Poupon et al.[5] ($S_{xo}$ = 100) | Wyllie et al.[4] and Perkins et al.[6] | de Witte Simplified Eq. 29 ($S_{xo}$ = 80) | de Witte Simplified Eq. 29 ($S_{xo}$ = 100) | White[7] and de Witte[9] Eq. 28 |
|---|---|---|---|---|---|---|---|
| 1. Average Calculated Hydrocarbon Saturations* for Hydrocarbon Zones | 62 | 59 | 52 | 41 | 70 | 64 | 53 |
| 2. Average Calculated Hydrocarbon Saturations* for Water Zones | 19 | 7 | 7 | 8 | 17 | 17 | 10 |
| 3. Difference [(1)-(2)] | 43 | 52 | 45 | 33 | 53 | 47 | 43 |

* Table 2.

TABLE 4 — EFFECT OF $S_{xo}$ ON POUPON ET AL.[5] AND DE WITTE[9] METHODS FOR CALCULATING HYDROCARBON SATURATIONS*

| Well | Sand | Poupon et al. $S_{xo}$ = 80% | Poupon et al. $S_{xo}$ = 100% | de Witte $S_{xo}$ = 80% | de Witte $S_{xo}$ = 100% |
|---|---|---|---|---|---|
| 2 | A | 75 | 71 | 87 | 84 |
| 3 | A | >90 | >87 | 95 | 93 |
| | B | 71 | 64 | 79 | 74 |
| | C | 35 | 46X | 64 | 56 |
| 4 | A | 90 | 87 | 93 | 90 |
| | B | 50 | 40X | 58 | 48X |
| | C | 63 | 56 | 75 | 70 |
| | D | 35X | 20X | 53 | 45X |
| 5 | A | 74 | 70 | 86 | 83 |
| | B | 57 | 48X | 73 | 67 |
| | C | 64 | 57 | 77 | 70 |
| | D | 0X | 0X | 6X | 0X |
| 6 | A | 74 | 70 | 87 | 84 |
| | B | 55 | 46X | 71 | 64 |
| | C | 38X | 27X | 58 | 48X |
| | D | 52 | 41X | 53 | 44X |

* Only hydrocarbon zones are considered here. $S_{xo}$ is the water saturation in the zone adjacent to the borehole (100-Residual Oil Saturation).

X Disagreement between known or expected production and calculated hydrocarbon saturation (50 per cent critical saturation is criterion).

From an exploration standpoint where $S_{xo}$ (water saturation in zone adjacent to borehole) is unknown, the reasonableness of the interpretation depends on the value assumed. In this case 80 per cent seems to result in adequate predictions. Table 4 shows the effect of using $S_{xo}$ = 100 per cent for the previously mentioned Poupon[5] and de Witte cases[9].

## Conclusions

1. Consideration of ionic layer effects by the de Witte and Patnode and Wyllie methods resulted in significant differences in calculated water saturations only when data were chosen to make these effects as large as possible. It is likely that ionic layer effects are not important in log interpretation of the formations studied.

2. Of the proposed interpretation methods, the Poupon, et al.[5] and simplified de Witte[9] methods differentiate hydrocarbon from water zones best, but probably could be improved by consideration of connate water saturation variations. For exploratory wells, the success of these methods for distinguishing hydrocarbon from water sands may depend on the $S_{xo}$ assumed.

3. The hypothesis that connate water saturation variations are partially responsible for the low resistivity log interpretation problem has been proposed and may apply in this field.

## Nomenclature

(All resistivities in ohm-meters.)

$R_w$ = Formation water resistivity

$R_o$ = Resistivity of sand, 100 per cent saturated with water

$F$ = Formation Resistivity Factor $\left(F = \frac{R_o}{R_w}\right)$

$F_a$ = Apparent Formation Resistivity Factor $F_a \rightarrow F$ as $R_w \rightarrow O$

$R_{cs}$ = "Conductive Solid" resistivity according to Patnode and Wyllie[2]

$S_w$ = Water saturation (per cent or fraction of pore volume which is water)

$S_H$ = Hydrocarbon saturation $(1 - S_w)$

$R_T$ = True formation resistivity

$n$ = Saturation exponent in Archie equation[11]

$$S_w^n = \frac{FR_w}{R_T}$$

$R_c$ = Conductive layer resistivity according to de Witte[3]

$X_w$ = Volume fraction of conductive clay-brine system which is water

$W_m$ = Volume fraction of sand system having connate water saturation $S_{w_m}$, 100 per cent water saturated resistivity $R_{om}$, and true

resistivity $R_{T_m}$ where $W_1 + W_2 + W_3 \ldots W_m = 1$

$R_{TA}$ = Apparent or average true resistivity for system (not necessarily apparent log resistivity)

$k_a$ = Air permeability (millidarcies)

$\phi$ = Porosity

$R_{xo}$ = Resistivity of invaded zone immediately next to the borehole (obtained from Microlaterolog[12] or Microlog[13] data)

SP = Self potential (millivolts)

$K$ = Constant in various shaly sand interpretation methods

$R_{mf}$ = Resistivity of mud filtrate

$S_{xo}$ = Water saturation in invaded zone close to the borehole

$T$ = Temperature

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## Appendix

Following is a description of the interpretation methods checked.

1. *Wyllie and Southwick*[4]

Using the equation $SP = K \log R_{xo}/R_o$ (symbols defined below) and knowing $SP$, $K$, and $R_{xo}$ solve for $R_o$ (see Fig. 8 of Wyllie's and Southwick's paper.[4])

$R_T$ was obtained from the lateral curve of the electrical survey. The Archie equation[11] $S^2 = R_o/R_T$ was used to solve $S$, $1 - S = H$.

$R_{xo}$ is the resistivity of the invaded zone immediately next to the borehole. It was obtained from Microlaterolog[12] or Micrologl[13] data.

$K$ is the constant (assumed to be 65).

2. *Poupon, Loy, and Tixier*[5]

$S_w$ is obtained from Fig. 5 of Poupon, Loy, and Tixier's paper.[5] To solve for $S$, it was necessary to know $R_{xo}$, $R_T$, $R_{mf}$, $R_w$ and $SP$, and assume $K$ and $S_{xo}$.

$R_{mf}$ is the mud filtrate resistivity and was obtained from page 16 of Schlumberger Well Surveying Corp. Document 5.

$R_w$ was obtained from measured data in the field.

$K$ was assumed to be 70.

$S_{xo}$ assumed to be 80 per cent in hydrocarbon zones.

3. *Perkins, Brannon, and Winsauer*[6]

From the equation $SP = 0.11\ (460 + T) \log R_{xo}/R_o$ it is necessary to obtain the formation temperature, $T$, to evaluate $K$. In the sands investigated, $T$ was about 155° $F$ or $K = 68$. Using a $K$ of 65, this method yields the same results as the Wyllie and Southwick method.

4. *White*[7]

This approach is a modification of the Perkins, et al. and Wyllie, et al. equations and is expressed as follows:

$$SP = 0.11\ (460 + T) \log \frac{R_{xo}}{R_T} \left( \frac{S_{xo}}{S} \right)^{2.15}.$$

$K$ will be 68 as mentioned above.

Assume $S_{xo} = 0.8$ for hydrocarbon zones.

Solution for $S$ is presented in Fig. 4.[7]

5. *de Witte*[8]

$$SP = K_t \left[ \log \frac{R_{xo}}{R_T} + \log \frac{S_{xo}}{S} \right]$$

$K_t = 0.2$ T where $T$ is the formation temperature (°$K$). In our case $K_t$ turns out to be 68. Assume $S_{xo} = 0.8$ for hydrocarbon zones. This equation (29 of Reference 9) applies to dirty sands.

De Witte also gives an equation (28 of Reference 9) which applies to relatively clean sands.

$$SP = K \left[ \log \frac{R_{xo}}{R_T} + 2 \log \frac{S_{xo}}{S} \right].$$

This can also be expressed as $SP = K \log \frac{R_{xo}}{R_T} \left[ \frac{S_{xo}}{S} \right]^2$.

With a $K$ of 68 this equation is identical with the White Equation 7 given above except that the exponent in the White paper is 2.15 instead of 2.

6. *Archie Equation*[11]

$$S^2 = \frac{R_{xo}}{R_{mf}} \frac{R_w}{R_T}$$

(Using $\frac{R_{xo}}{R_{mf}}$ instead of measured formation factor, $F$.)


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★★★

FEATURE ARTICLE

# HIGH STRENGTH GRANULAR SEALING MATERIAL INCREASES EFFICIENCY of PRIMARY CEMENTING and SQUEEZE CEMENTING

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## Abstract

*The use of high strength granular materials in cement slurries has proved beneficial for cementing casing and squeeze cementing operations in Permian Basin oil and gas wells. The addition of 1 to 4 lb of ground walnut shells to each sack of cement made possible successful high column cementing jobs in fields where high fill-ups normally cannot be obtained because of lost circulation. In squeeze cementing operations the number of cementing stages required for shutting off water was reduced by the addition of walnut shells to the last 50 per cent of the volume of cement slurry.*

## Introduction

The high hydrostatic head, created in the annulus when cementing casing, frequently is the cause of loss of slurry into weak formations or formations containing fractures or vugs. Common precautions taken to reduce this loss are reducing the density of the slurry, adding effective sealing agents to the slurry, or both.

One phase of this paper concerns the use of high strength granular sealing materials in cement slurry to seal openings into formations so that the slurry may be pumped to the desired level behind the casing.

In squeeze cementing operations neat cement often fails to effect a complete seal because of the tendency of the slurry to enter only the weakest zones. This is indicated by the number of stages frequently required to stop the flow of water or gas. The intrusion of cement slurry into each perforation in a water or gas producing zone is probably necessary to eliminate flow completely, and a high final squeeze pressure may be a means of assuring entry of cement into each perforation or zone of weakness.

The second phase of this paper concerns the use of high strength granular materials in cement slurries to obtain a high final squeeze pressure.

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## Investigation

To withstand the high differential pressure incurred during high column and squeeze cementing operations, a high strength sealing agent compatible with cement was sought. Such a material was found described in the literature.[1] The results of fracture sealing tests which were presented (see Fig. 1) indicated that among a large number of materials tested, ground and graded walnut shells sealed the largest size fracture against the greatest differential pressure. This observation was substantiated through data presented by W. F. Rogers.[2]

The compatibility of this sealing agent with cement was determined by strength tests on several Portland and slo-set cements. The results of these tests are presented in Table 1.

To determine the application of the high strength sealing agent[1,2] to casing and squeeze cementing operations, field tests were initiated in areas where casing and squeeze cementing operations were often difficult.

TABLE 1 — 24 HOUR TENSILE STRENGTHS OF CEMENTS CONTAINING BLACK WALNUT SHELLS

| | Concentration of Walnut Shells—Lb/Sack | | |
|---|---|---|---|
| | 0 | 1 | 2 |
| Cured at 120°F. | | | |
| Portland Cement A | 256 psi | 229 psi | 200 psi |
| Portland Cement B | 236 | 207 | 159 |
| Portland Cement C | 194 | 147 | 136 |
| Slo-set Cement A | 127 | 96 | 87 |
| Cured at 180°F. | | | |
| Slo-set Cement B | 318 | 244 | 160 |
| Slo-set Cement C | 220 | 167 | 118 |

| | Temp. °F. | Concentration of Walnut Shells—Lb/Bbl | | | |
|---|---|---|---|---|---|
| | | 0 | 12 | 20 | 40 |
| Cement D | 120 | 293 psi | 221 psi | 219 psi | 206 psi |
| | 160 | 457 | 329 | 283 | 355* |
| | 180 | 378 | 365 | ..... | ..... |
| Cement E | 120 | 447 | ..... | 266 | 217 |
| | 160 | 560 | ..... | 330 | 239 |
| | 180 | 450 | ..... | 346 | ..... |
| Cement F | 160 | 361 | ..... | 208 | 167 |

*72 hours

[1]References given at end of paper.

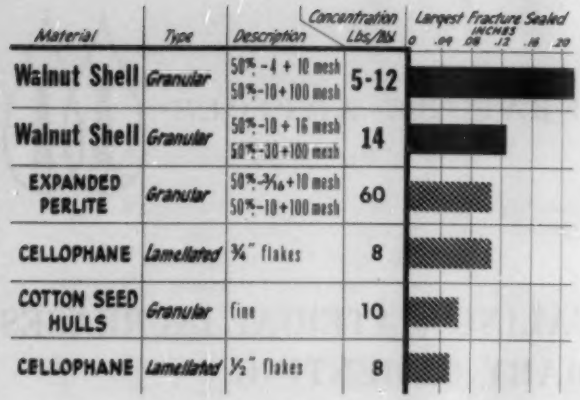


Fig. 1 — Sealing ability of additives.[3]

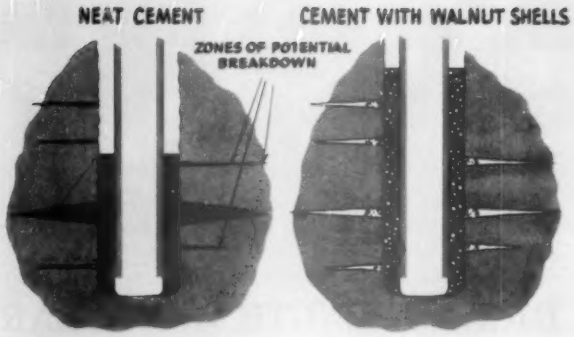


Fig. 2 — Plugging action of walnut shells to prevent loss of cement slurry while cementing casing.

## Results and Discussion

### High Column Cementing

Cement slurry containing walnut shells was used to set pipe in approximately 80 wells in fields where lost circulation normally occurred. In each of these 80 wells the fill was increased by 700 ft to 2,200 ft above the fill achieved in adjacent wells using neat or gel cement alone or with flaked additives and expanded mineral.

Three different grinds of walnut shells were used in these tests:

| | |
|---|---|
| Coarse grind: | 50 per cent −4 + 10 mesh<br>25 per cent −10 + 40 mesh<br>25 per cent −40 + 100 mesh |
| Medium grind: | 50 per cent −10 + 16 mesh<br>50 per cent −16 + 100 mesh |
| Fine grind: | −30 + 100 mesh |

From 1 to 4 lb of shell were mixed with cement either at the hopper or at the bulk cement plant. The shells were pumped in either neat cement or 2 to 14 per cent gel cement. Fourteen per cent water by weight of shell was required to compensate for the water used in wetting the surface of the shells. There were no indications of changes in the flow properties of the cement slurries by the presence of the shells.

In Table 2 are shown the properties of slurries of neat cement, 4 per cent gel cement, 4 per cent gel cement containing walnut shells, and 4 per cent gel cement containing expanded mineral.

It may be seen in Table 2 that the addition of a small concentration of shell to a slurry may provide a means of obtaining a high fill-up when cementing pipe through lost circulation zones.

Forming a high strength seal in openings into formations is probably a requisite for high cement fills when cementing casing through lost circulation zones. It may be seen in Fig. 2 how walnut shells may seal fractures so as to prevent loss of cement slurry and provide a higher cement fill-up.

Table 3 depicts the results of high column casing cement operations performed in a West Texas Ellenburger field. Similarly, Tables 4 and 5 depict the results of casing cement operations in a West Texas Clearfork field, and a West Texas Strawn field, respectively. In all cases it may be seen that higher fill-ups were obtained through the use of walnut shells.

TABLE 2 — PROPERTIES OF CEMENT SLURRIES

| | Neat Cement | 4% Gel Cement | 4% Gel Cmt. w/1 lb Walnut Shells/sack (coarse grade) | 4% Gel Cmt. w/1 cu ft Expanded Mineral/sack |
|---|---|---|---|---|
| 1. Water Cement Ratio (gal/sk) | 5.50 | 7.70 | 7.72 | 12.00 |
| 2. Specific Volume (cu ft/sk at 3,000 psi) | 1.22 | 1.535 | 1.550 | 2.20 |
| 3. Slurry Weight lb/gal | | | | |
| At atmos. pressure | 15.4 | 14.10 | 14.05 | 11.68 |
| At 3,000 psi | 15.4 | 14.10 | 14.05 | 12.79 |
| 4. Compressive Strength (psi)* | 2,400 | 2,100 | 2,000 | 800 |
| 5. Tensile Strength (psi)* | 265 | 200 | 190 | 80 |
| 6. Lb/bbl Sealing Agent | 0 | 0 | 3.63 | 33.2 |
| 7. Maximum Size Fracture Sealed (inches) | | | | |
| At 300 psi | .01 | .01 | .19 | .10 |
| At 1,000 psi | .01 | .01 | .19 | .08 |
| At 3,000 psi | .01 | .01 | .19 | .03 |
| 8. Strength of Seal (psi)** | 0 | 0 | 3,000+ | 300 |
| 9. Additional Cement Fill-up due to additive (ft)*** | 0 | 0 | 4,100+ | 450 |

*Cured for 24 hours at 120°F.

**Differential Pressure withstood by seal across 0.1 in fracture

***Calculated from lines 3, 7, and 8.

TABLE 3 — RESULTS OF HIGH COLUMN CEMENTING OPERATIONS ELLENBURGER FIELD — WEST TEXAS

| CEMENT AND ADDITIVES USED | | | |
|---|---|---|---|
| 6% Gel-Sloset Cement | 778 sk(Avg.) | 6% Gel-Sloset Cement | 1,275 sk (Avg.) |
| Expanded Mineral | 789 cu ft (Avg.) | Walnut Shells (−10 + 100 mesh) | 2 lb/sk |
| Plastic Flakes | ¼ lb/sk (Avg.) | | |
| Neat Cement | 108 sk (Avg.) | Neat Cement | 100 sk (Avg.) |
| Number Wells | 9 | 4 | |
| Hole Size | 7⅞—8¾ in | 7⅞—8¾ in | |
| Casing Size | 5½—7 in | 5½—7 in | |
| Casing Depth (Avg.) | 12,658 ft | 12,511 ft | |
| Top of Cement (Avg.) | 8,361 ft | 5,670 ft | |
| Actual Fill (Avg.) | 4,296 ft | 6,841 ft | |
| *Theoretical Fill (Avg.) | 10,877 ft | 11,628 ft | |
| Per Cent Theoretical Fill (Avg.) | 40.7 | 59.5 | |

*Based on gauge hole.

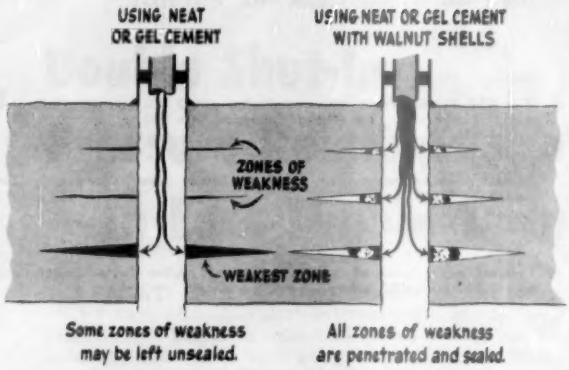
USING NEAT OR GEL CEMENT
USING NEAT OR GEL CEMENT WITH WALNUT SHELLS
ZONES OF WEAKNESS
WEAKEST ZONE
Some zones of weakness may be left unsealed.
All zones of weakness are penetrated and sealed.

Fig. 3 — Function of walnut shells in cement slurry when squeeze cementing.

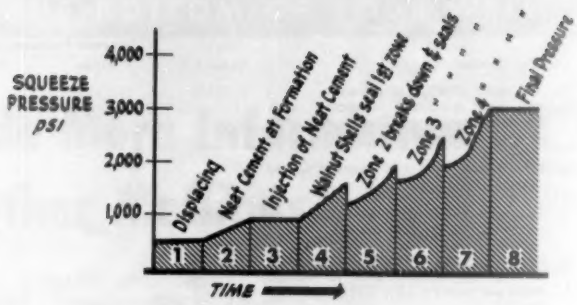


Fig. 4 — Pressures observed during typical squeeze cementing operation with cement containing walnut shells.

### Squeeze Cementing

The technique developed for employing granular materials in squeeze cementing operations consisted of adding a concentration of 4 to 8 lb of walnut shells per sack of cement to the last 50 per cent of the cement slurry squeezed into a gas or water producing zone. The purpose of the granular material was to provide a strong seal in the first section into which the neat cement entered so that cement could be forced into other sections (Fig. 3). In perforated sections the pattern was believed to be a series of breakdowns and seals through each perforation, one-by-one, until all perforations were sealed.

In Fig. 4 are shown the pressures observed during a typical walnut shell-cement squeeze job.

Ground and graded walnut shells (coarse or medium grind) were used as the granular sealing material in all tests. The technique was used on a total of 60 wells, with 54 being successful on the first stage.

Following are the details of three typical tests.

### West Dollarhide Field

A perforated interval from 6,914 to 6,940 ft produced 339 bbl of salt water in 17 hours on a swab test following a 2,000 gal acid treatment. One hundred sacks of cement containing 12 lb of granular material (walnut shell) per sack were squeezed into the perforations below a drillable retainer set at 6,885 ft. A pressure of 3,750 psi was developed after 29 sacks of cement were displaced into the formation. The well was then perforated from 6,734 to 6,846 ft and completed for 156 BOPD and no water. In subsequent applications, the use of granular material was confined to the last 50 per cent of the slurry so that more neat cement could be forced into the weakest section.

### Ellenburger Field, West Texas

Details of this test appear in Table 6.

### West Texas Wildcat

Details of this test appear in Table 7. The use of granular material in cement was successful in shutting

TABLE 4 — RESULTS OF CASING CEMENTING OPERATIONS—WEST TEXAS CLEARFORK FIELD

| | CEMENT AND ADDITIVES USED | | | |
|---|---|---|---|---|
| | 2 per cent Gel Cement and Pozzolan (50:50) | 1,912 sk (Avg.) | 8% Gel Cement | 370 sk (Avg.) |
| | | | 8% Gel Cement + 1 lb/sk walnut shells ( − 10 + 100 mesh) | 1,150 sk (Avg.) |
| | | | 2% Gel Cement and Pozzolan (50:50) | 200 sk (Avg.) |
| Number Wells | 4 | | 7 | |
| Hole Size | 8¾ in | | 8¾ in | |
| Casing Size | 7 in | | 7 in | |
| Casing Depth (Avg.) | 6,452 ft | | 6,445 ft | |
| Top of Cement (Avg.) | 3,064 ft | | 2,551 ft | |
| Fill (Avg.) | 3,388 ft | | 3,894 ft | |
| Remarks: | Lost circulation during displacement<br>Recemented 2 wells with 725 sk cement each | | Full returns | No recementing necessary |

TABLE 5 — RESULTS OF CASING CEMENTING OPERATIONS — WEST TEXAS STRAWN FIELD

| | CEMENT AND ADDITIVES USED | | | |
|---|---|---|---|---|
| | 4% Gel Cement + Pozzolan (50:50) Expanded Mineral | 500 sk<br>300 cu ft | 6% Gel Cement + Pozzolan (50:50) Walnut Shells* | 536 sk (Avg.)<br>2lb/sk |
| | | | 2% Gel Cement + Pozzolan (50:50) | 50 (Avg.) |
| Number Wells | 1 | | 7 | |
| Hole Size | 7⅞ in | | 7⅞ in | |
| Casing Size | 5½ in | | 5½ in | |
| Casing Depth (Avg.) | 6,582 ft | | 6,410 ft | |
| Top of Cement (Avg.) | 4,510 ft | | 3,654 ft | |
| Fill (Avg.) | 2,072 ft | | 2,756 ft | |
| Theoretical Fill (Avg.)* | 5,080 ft | | 5,176 ft | |
| % Theoretical Fill (Avg.) | 40.7 | | 53.1 | |

*Based on Gauge Hole

*2 wells — coarse grind
5 wells — medium grind

TABLE 6 — USE OF HIGH STRENGTH GRANULAR MATERIAL IN SQUEEZE CEMENTING ELLENBURGER FIELD, WEST TEXAS

The production string was cemented as follows:

| Sacks of Cement | Top of Cement | Squeeze Pressures (psi) Initial | Final | Remarks |
|---|---|---|---|---|
| 1. 400 sacks of 6% gel cement . . . 400 cu ft expanded mineral. 1/4 lb flaked material per sack plus 100 sacks neat cement | 8,835 ft | | | 7 in CSA 12,565 ft and cemented. Tested with 2,200 psi. OK. Perforated 8,750-51 w/4 shots. Established circulation with 900 psi. |
| 2. Recemented with 175 sacks 6% gel cement . . . . . | 7,615 ft | | | Cemented below retainer at 8,720 ft. Drilled retainer and plug. Set packer at 8,690 ft. |
| 3. Squeezed perforations at 8,750-51 ft w/100 sk Slo-set neat cement . . . | | 1,800 | 1,400 | Unsuccessful. Washed perforations. WOC 8 hrs. |
| 4. Resqueezed 1w/100 sk Slo-set neat 50 sk 4% gel cement w/4 lb walnut shells per cent (- 10 + 100) (medium) per sack . . . . . | | 2,000 | 4,100 | Reversed out 1.5 bbl of cement. Drilled out packer. Tested perforations with 2,000 psi for 30 minutes. Held. Successful. |

TABLE 7 — USE OF HIGH STRENGTH GRANULAR MATERIAL IN SQUEEZE CEMENTING WILDCAT WELL, WEST TEXAS

7 in casing was set at 13,951 ft with 150 sacks of Slo-set cement. A drill stem test of the interval 14,187-14,325 ft yielded 2,700 ft water blanket, 270 ft water cut mud, and 5,625 ft salty sulphur water. Cementing operations that followed are listed below:

| Sacks of Cement | Max. Sq. Pressure | Remarks |
|---|---|---|
| 1. 20 sack plug . . . . . | | Set open hole bridge plug at 14,125 ft and spotted 20 sacks cement above plug. Found no cement above plug. Pushed bridge plug down to 14,142 ft with 3,000 psi. |
| 2 30 sack plug . . . . . | | Top of cement 13,997 ft. Drilled out to 14,000 ft. Acidized 13,950-14,000 ft w/1,500 gal mud acid. Breakdown pressure 5,300 psi. Acid-fraced w/3,000 gal w/2 lb sand/gal. Inj. rate 2 BPM at 5,600 psi. Swabbed 100% water. Fluid level 1,000 ft from the surface. |
| 3. Squeezed w/150 sacks Slo-set Cement . . . . . | | Set DM squeeze tool at 13,924 ft. Unable to get squeeze pressure. Cleared tool. WOC 4 hours. |
| 4. Resqueezed w/100 sacks Slo-set and 100 sacks Slo-set containing 4% gel w/4 lb walnut shells per sacks . . . | 5,800 psi | Reversed out 20 sacks. Drilled out retainer and cement plug to 13,965 ft. Attempted to acidize below 13,912 ft but packer failed at 4,000 psi. Reran packer at 13,913 ft and acidized w/1,500 gal reg. acid at 5,400 psi. Reacidized w/3,000 gal acid. Tubing pressure 5,400-4,500 psi. Flowed 15 bbl of fluid per hour, 98% water. Killed well. Set retainer at 13,947 ft. |
| 5. Squeezed w/150 sk Slo-set and 100 sk of 4% gel cement containing 4 lb walnut shells per sack . . . . . | 5,800 psi | Reversed out 75 sk. Perf. 13,930-13,944 ft w/2 Jet shots/ft. Acidized below 13,899 ft w/3,000 gal acid. Tubing pressure 6,500-4,000 psi. Swabbed 113 BW in 11 hrs. Fluid level 1,500 ft from surface. |
| 6. Squeezed w/150 sk Slo-set and 100 sk Slo-set 4% gel cement containing 4 lb walnut shells per sack . . . . . | 5,900 psi | Reversed out 48 sacks. |

off water in artificially fractured open-hole Ellenburger formation after two plug-backs and one squeeze job with neat cement had failed.

## Conclusions

1. The results of 80 casing cementing field tests indicated that the addition of 1 to 4 lb of high strength granular material (graded walnut shells) to each sack of cement provides a means for conducting successful high column cementing operations in areas where high fill-ups normally cannot be obtained because of lost circulation.

2. The results of 60 squeeze cementing field tests indicated that the number of cementing stages required to shut off the flow of undesirable fluids may be reduced by the addition of 4 to 8 lb of high strength granular material (walnut shells) to each sack of cement of the last 50 per cent of the volume of cement slurry.

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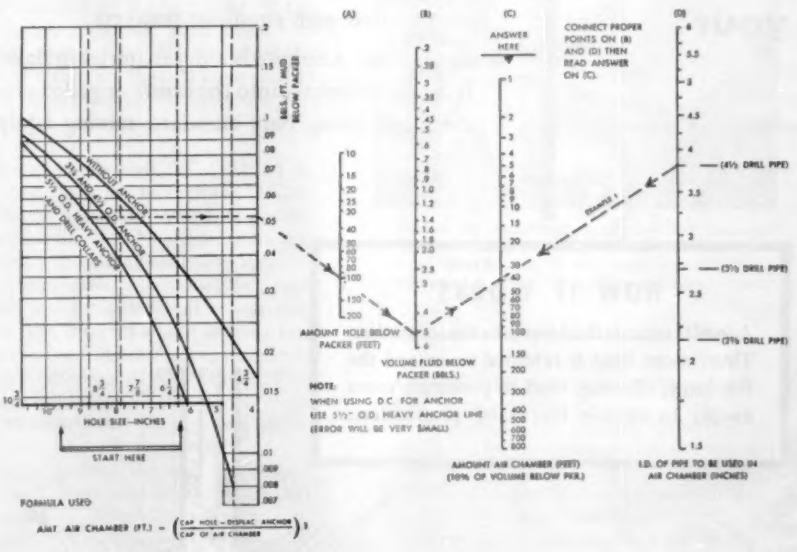
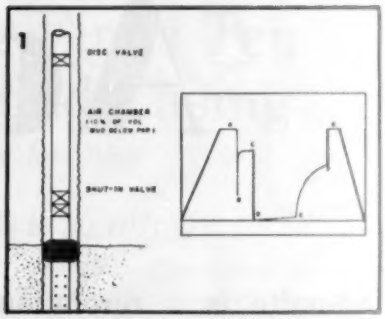
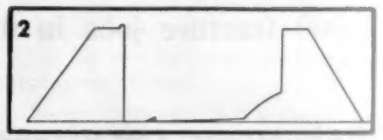
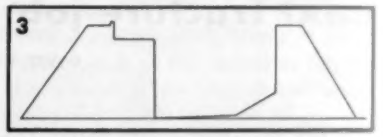

(A)
(B)
(C)
(D)
ANSWER HERE
CONNECT PROPER POINTS ON (B) AND (D) THEN READ ANSWER ON (C).
BBLS. FT. MUD BELOW PACKER
HOLE SIZE—INCHES
START HERE
AMOUNT HOLE BELOW PACKER (FEET)
VOLUME FLUID BELOW PACKER (BBLS.)
EXAMPLE
(4½ DRILL PIPE)
(3½ DRILL PIPE)
(2½ DRILL PIPE)
NOTE:
WHEN USING D.C. FOR ANCHOR USE 5½" O.D. HEAVY ANCHOR LINE (ERROR WILL BE VERY SMALL)
AMOUNT AIR CHAMBER (FEET) (10% OF VOLUME BELOW PKR.)
I.D. OF PIPE TO BE USED IN AIR CHAMBER (INCHES)
FORMULA USED
AMT AIR CHAMBER (FT.) = (CAP. HOLE − DISPLAC. ANCHOR / CAP. OF AIR CHAMBER) × 1



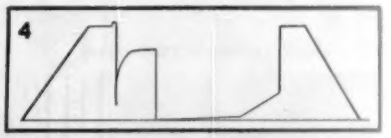

Testing tool assembly for double shut-in pressure readings which permits a limited fluid withdrawal. By placing the disc valve above the main or hydraulic valve so that a specified volume of air is trapped between these two valves.




Well not capable of producing fluid fast enough to fill up air chamber and cause pressure build-up.




Mud did not expand enough to get pressure draw-down below the formation pressure.




Mud expanded and pressure draw-down was below the formation pressure. Well was able to flow enough fluid to fill up air chamber and build-up shut-in pressure.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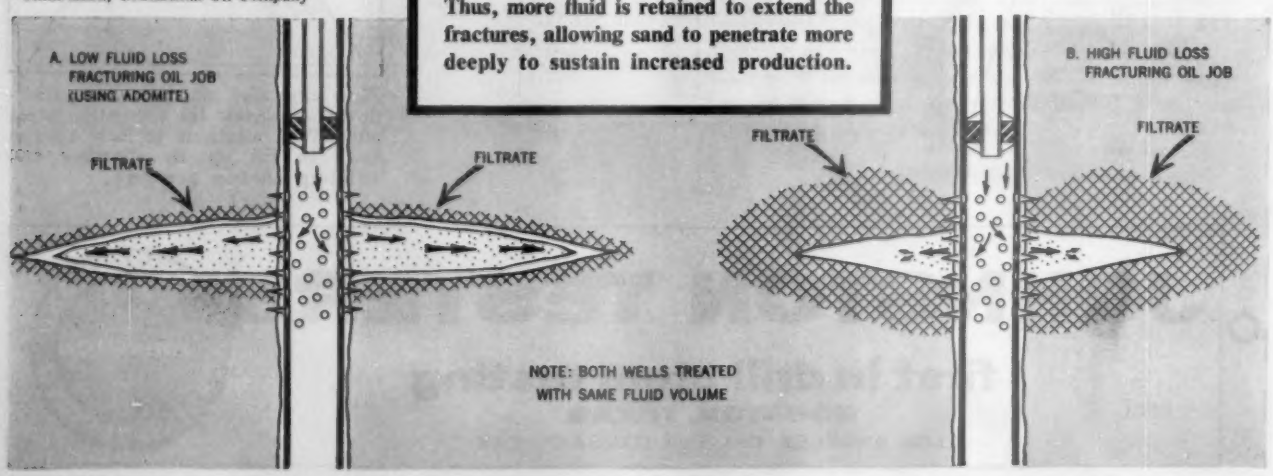

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A fine example of the accuracy of the McCullough Radiation Well Logger in locating, defining and interpreting the nature of a thin productive zone so that it could be perforated for maximum production, has just been reported from a Kansas oil field.

This was a new well. 5½″ O.D. 14 lb. casing had been set to bottom. McCullough ran a Radiation Well Log obtaining Gamma Ray and Neutron curves and recording a simultaneous collar log.

The log revealed a thin, four foot zone at 3856′ and indicated that it was productive. The interval was shot from logging curves and collar log measurements with McCullough's 4″ O.D. Super Casing Glass Jets in Steel Strip Carrier, four holes per foot. Total logging and perforating time was only three hours.

After perforating, the well had a good show of oil. Zone was treated with acid and made 240 barrels per day on test, which was a very good well for the field.

The McCullough Radiation Well Logger is the most accurate, reliable and efficient logging instrument available. It has greater stability, provides more detail and assures more accurate quantitative interpretation.

Because of the extreme efficiency of the scintillation counter in detecting radiation and because of its very short length, it is possible to log beds as thin as 12″ with clarity and accuracy.

Whether the pay zone be thick or thin, the simultaneous recording of a collar log means placing the perforations exactly where they are wanted . . . fully covering the productive formation.

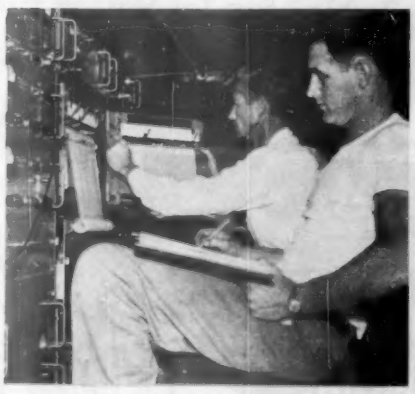
# McCullough Log Finds Ten Feet of Pay Behind Casing

### *Sixteen Standard Casing Glass Jets Shot in 10′ of Cased Off Pay Zone Increase Production from 5 B/D to 30 B/D*

Many times the McCullough Radiation Well Logger has been instrumental in turning a poor producer into a profitable operation. While this Oklahoma well was a small producer even at its best, the 500% increase in production gained through the use of McCullough Logging and Perforating Services meant the difference between loss and profit.

The operator had set 4½″ O.D. 9.5 lb. casing on top of the pay zone. The interval was treated but the resulting 5 barrels per day of production was considerably below the average for the field.

McCullough was called to run their Radiation Well Logger. Gamma Ray and Neutron curves were obtained along with a simultaneous collar log. It was found that 10′ of pay zone lay behind the casing at approximately 1645′.



Interior of McCullough Radiation Well Logging Truck showing electronic instrumentation, controls, recorder, etc. At this panel down-hole information is evaluated and recorded with extreme accuracy.

Sixteen shots were fired in the 10′ interval by a McCullough Standard Casing Glass Jet Perforator with Steel Strip Carrier. The well is now making 30 barrels per day—a good well for the field. Total time on the job for both logging and perforating was one hour, twenty minutes.

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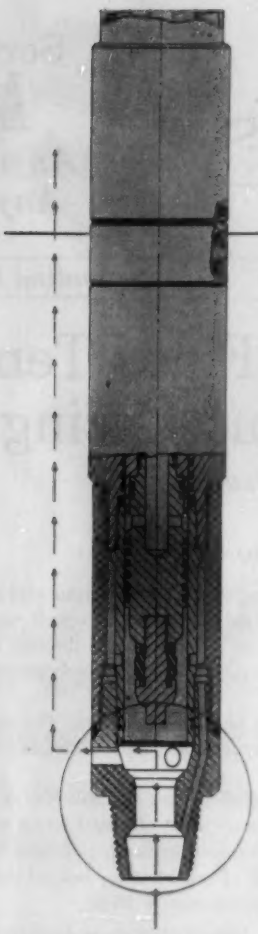

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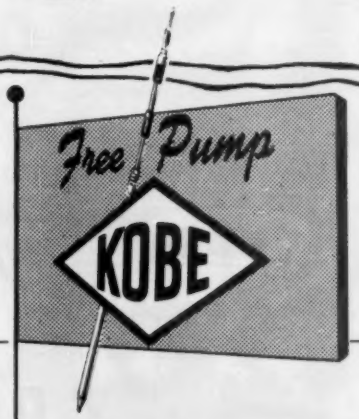


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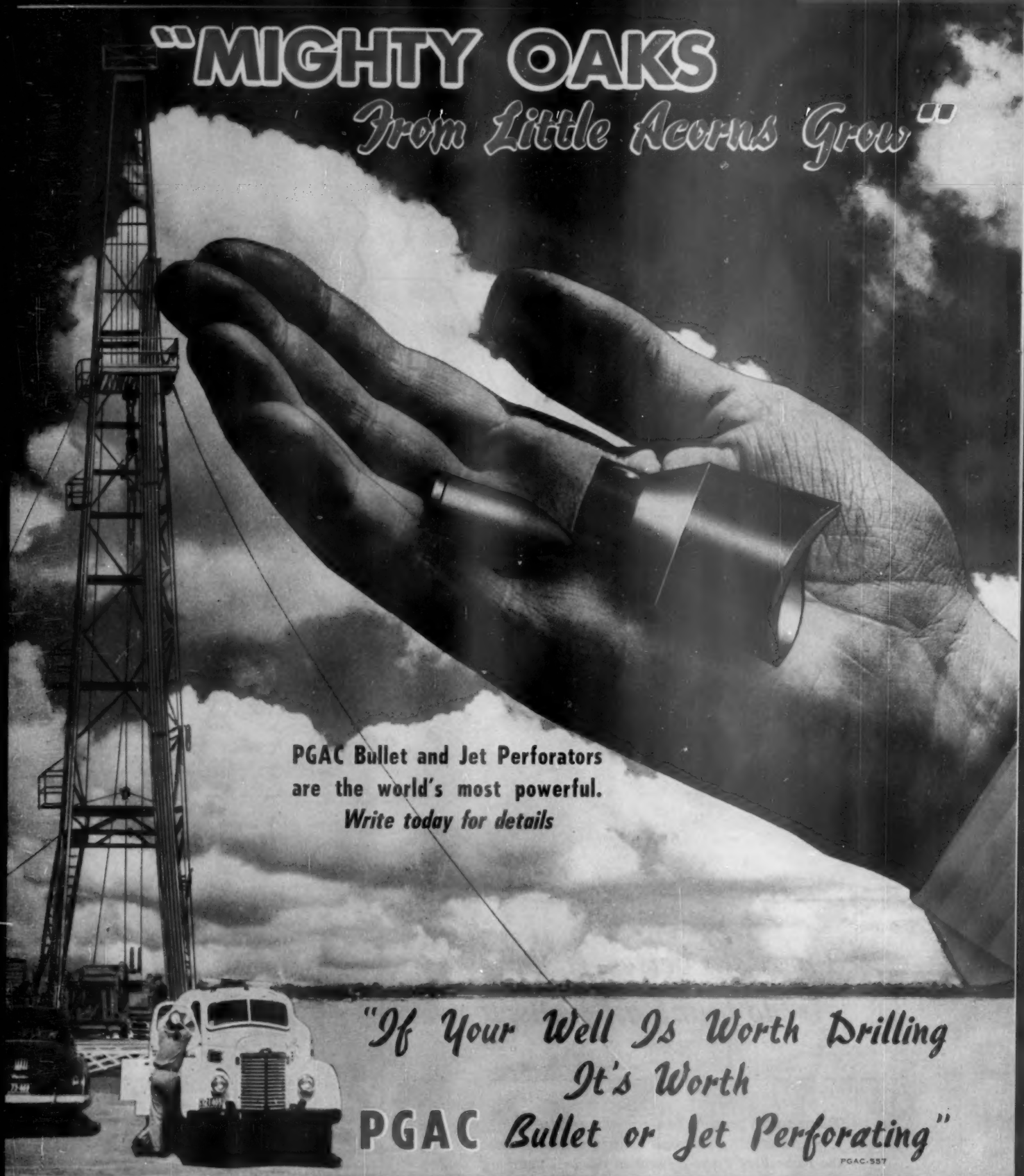

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# CANAL FIELD GAS INJECTION PROJECT

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W. TEMPELAAR-LIETZ

SHELL OIL CO.
LOS ANGELES, CALIF.

## Abstract

*For the history of the performance of the Canal field gas injection project reference is made to two publications.*

*In the present paper a critical examination has been made of the pressure measurements and of the pressure-volume-temperature data for the reservoir fluid.*

*Material balance calculations were employed to determine the oil in place, the size of the oil reservoir, the size of the aquifer, the amount of water inflow, and the migration of hydrocarbons within the reservoir. The effectiveness of the gas-injection program is discussed.*

## Introduction

The gas injection project in the Canal field, San Joaquin Valley, Calif., has now a history of 14 years. The performance was discussed in a paper presented by R. P. Mangold before the Pacific Coast District API meeting in Los Angeles, April 11, 1946. This paper was not published, but the pertinent data have been recapitulated by Muskat[1]. In July, 1952, the Bureau of Mines published their Report of Investigations No. 4886[2] in which an excellent review of the history up to that time is presented, and the reader is referred to that publication.

In the present paper a short resume of the history is shown in Figs. 1 through 4. In the last paragraph of the Bureau of Mines' publication reference is made to the gas injection in Well E-11. The additional information on this localized injection now available is presented in the next section.

The remainder of the present paper will deal with the technical methods used in a detailed analysis of the various aspects of this project.

## A Localized Injection Experiment

Wells A47-14, E-11, and E-14 are located on the southern flank of the field. In the 24 months preceding April, 1948, E-11 flowed 7,541 bbl of oil at an average rate of 12 B/D. In the same period, A47-14 and E-14 pumped 7,510 bbl and 17,798 bbl, respectively, at

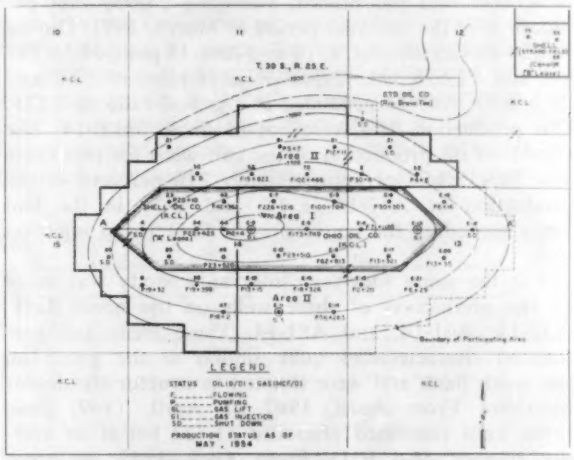


**Fig. 1 — Structural contours and production status of the wells. The Area I-Area II boundary represents a separation of the field into two sections for the purpose of studying internal hydrocarbon movement.**

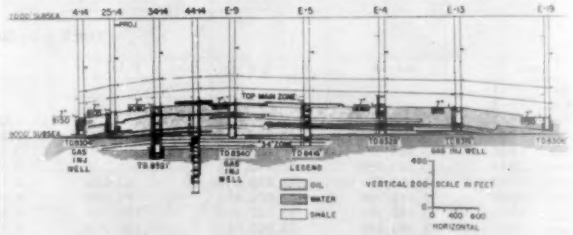


**Fig. 2 — Longitudinal cross section.**

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Paper presented at Pacific Petroleum Chapter Fall Meeting in Los Angeles, Oct. 7-8, 1954. Original manuscript received in Petroleum Branch Office on Sept. 9, 1954. Revised manuscript received June 10, 1955.

[1]References given at end of paper.

*C. J. Pings, Jr., has received his PhD degree and is now a member of the faculty of Stanford University.

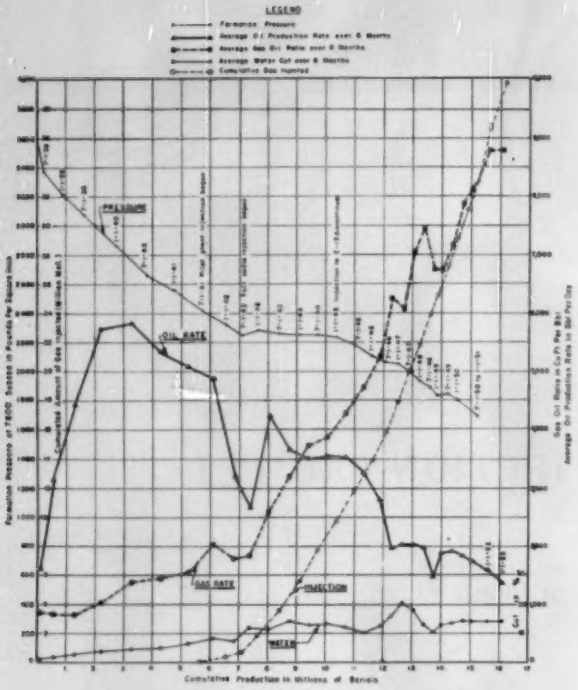


**Fig. 3 — Performance history.**

rates of 38.6 and 11.7 B/D with gas-oil ratios of 1,441 and 1,582 cu ft/bbl. In this two-year period these three wells combined produced 32,849 bbl of oil.

In April, 1949, E-11 was converted to an injection well and gas was injected at rates varying from 9,000 to 45,000 Mcf per month, averaging 24,000 Mcf per month over the two-year period to March, 1951. During this 24-month interval, E-14 and A47-14 pumped 58,197 bbl and 12,638 bbl, respectively, at rates of 82.2 and 26.2 B/D. A47-14 produced at a gas-oil ratio of 2,275. Gas production data were not available for E-14. The combined oil production of the two wells for two years was 70,835 bbl, or approximately 216 per cent of the production of A47-14, E-14, and E-11 in the two years preceding the conversion of E-11 to an injection well.

For the same four-year interval, a study was made of the production of three wells on the north flank, A32-14, A61-14, and A81-14. These wells had production characteristics quite similar to the group on the south flank and were situated in structurally similar locations. From April, 1947, to April, 1949, these three wells combined produced 31,723 bbl at an average rate of 43.4 B/D. From April, 1949, to April, 1951, the average rate was 15.7 B/D for a total production of 11,469 bbl, a decline of 64 per cent over the 1947 to 1949 interval. These production data are compared in Fig. 4.

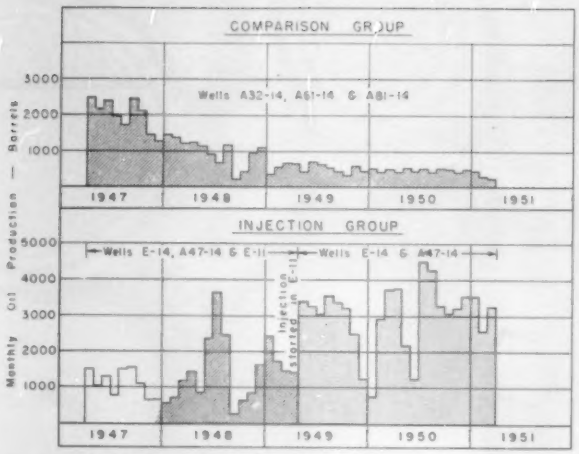


**Fig. 4 — Production from E-11 injection group and three comparison wells.**

It appears that the injection in E-11 has resulted in some additional recovery of oil. If it were assumed that the three wells, E-11, E-14, and A47-14, would have demonstrated the same decline as the wells on the north flank if injection had not been started in E-11, then the additional recovery during the two-year interval could be fixed at about 59,000 bbl or 180 per cent. More conservatively, if it were assumed that without injection these wells would have produced during 1949 to 1951 the same as they did in 1947 to 1949, then the additional recovery is about 38,000 bbl, or 116 per cent. Gas-oil ratios appeared to have increased by about 50 per cent in this period. Even as late as the first four months of 1953, wells A47-14 and E-14 produced at average rates of 16.9 and 42.1 B/D, still in excess of the preinjection rates.

## Volumetric and Phase Behavior of Reservoir Fluid

PVT data were available for five samples. In general, the gas-oil ratio, the total composition, the relative volume of the gas phase, and the relative volume of the liquid phase had been determined for each sample. These data were broken down for each sample to establish the dependence on pressure of three quantities: (a) liquid phase volume, (b) gas phase volume, and (c) gas in solution. For each of these three intensive properties values were selected which were thought to be most representative of the five samples. The latter were in turn recombined to give a composite representation of the volumetric and phase behavior of the reservoir hydrocarbon fluid. Conflicting data were resolved in an unbiased manner by fitting quadratic equations by the method of least squares. The uncertainties introduced by utilizing such equations were found to be

TABLE 1 — GAS INJECTION DATA

| Date | A4-14 | E-9 | E-11 | E-13 | Field Total | Remarks |
|---|---|---|---|---|---|---|
| June 1941 | | | | | | Start of pilot injection in E-9. |
| Aug. 1942 | | 887,160 | | 66,531 | 953,691 | Start of full scale injection in E-9 and E-13. |
| May 1943 | 5,562 | 2,261,673 | | 1,000,413 | 3,267,648 | Start of injection in A4-14. |
| Feb. 1945 | 612,266 | 6,225,603 | | 3,552,045 | 10,389,914 | Injection stopped in E-13. |
| Feb. 1948 | 3,264,870 | 15,620,129 | | 3,552,045 | 22,446,032 | Includes 8,988 Mcf injected into A25-14. Suspended. |
| Nov. 1948 | 3,553,952 | 17,713,248 | | 3,578,842 | 24,855,030 | Injection resumed in E-13. |
| April 1949 | 3,587,507 | 18,813,842 | 45,096 | 4,113,768 | 26,587,201 | Start of injection in E-11. |
| May 1949 | 3,590,290 | 19,008,405 | 79,590 | 4,195,623 | 26,882,896 | No gas entry into A4-14 after this date. |
| Oct. 1951 | 3,590,290 | 25,127,566 | 729,167 | 6,652,996 | 36,109,007 | |
| May 1953 | 3,590,290 | 28,903,703 | 1,141,738 | 8,051,583 | 41,696,302 | |
| May 1954 | 3,590,290 | 31,214,426 | 1,531,569 | 8,659,305 | 45,004,678 | |

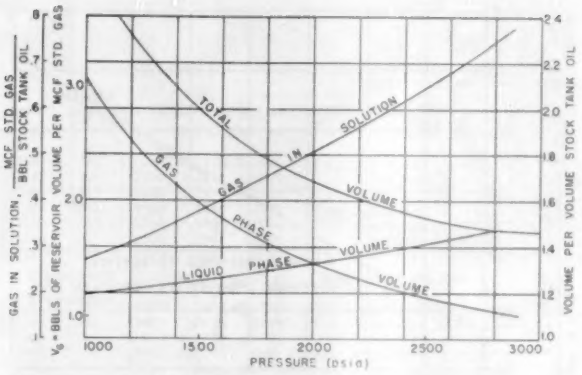


**Fig. 5 — PVT data.**

small in comparison with the errors and inconsistencies of the experimental data.

The following equations were used to describe the behavior of the reservoir fluid:*

$$V_L = 1.0938 + 0.07974 \times 10^{-2} P + 0.02040 \times 10^{-6} P^2 \quad [P \leq P_b] \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$V_G = \frac{1}{-0.05691 + 0.3844 \times 10^{-2} P - 0.007181 \times 10^{-6} P^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$r = 0.1044 - 0.1324 \times 10^{-3} P + 0.03476 \times 10^{-6} P^2 \quad [P \leq P_b] \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$V_L = 1.553 - 0.0267 \times 10^{-3} P \quad [P \geq P_b] \quad . \quad . \quad (4)$$

$$V_{L_o} = 1.463 \text{ bbl/bbl stock tank oil} \quad . \quad . \quad . \quad . \quad (5)$$

$$r_o = 0.750 \text{ Mcf/bbl stock tank oil} \quad . \quad . \quad . \quad . \quad (6)$$

$$P_b = 2{,}810 \text{ psia} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Fig. 5 shows a composite representation of the PVT data. The original gas-oil ratio was determined from the initial production of the early wells in the field. The bubble point pressure of 2,810 psia was found by solving Equation 3 for the value of pressure corresponding to this original gas-oil ratio of 0.750 Mcf/bbl. One of the five original sets of data had been obtained for a sample recombined at this ratio; the experimentally reported value for bubble point pressure was also 2,810 psia.

## Pressure Data

Pressure surveys were, in general, made annually and usually involved measurements from about 20 wells, although the same wells were not always represented in each survey. Pressures at the mid-point of the pay have been employed rather than at datum plane since the former are required for the material balance calculations. At any given date, the sample of pressures obtained showed ranges up to 800 psi, approximately 40 per cent of the median pressures. Obtaining from such a set of data a single number which best represents the entire reservoir presents a significant problem.

Three types of uncertainties were recognized: (a) errors in the pressure measuring instruments, (b) errors due to incorrect weighting of the observed data, and (c) errors introduced by representing the entire reservoir by data obtained from a small number of finite sectors of the reservoir.

It was estimated that random instrument errors would contribute uncertainties of about 0.25 per cent to an arithmetic average of 16 observations and that errors from weighting did not exceed 0.25 per cent. The average of a finite number of readings is limited, in addition, by the precision or reproducibility of the average. In order to obtain some information regarding this precision, an investigation was made of the degree and nature of the dispersion of the experimental pressure data. For each year, the arithmetic average pressure and deviations from the mean for the entire reservoir were calculated. Deviation data for the pressure surveys covering a seven-year period were then tabulated in order of magnitude and the relative frequencies of occurrence were calculated. Frequency data are plotted in Fig. 6 on arithmetic probability graph paper, which has one coordinate axis so adjusted that a plot of data conforming to a normal probability distribution will form a straight line. Pressure data from the Canal field show a definite indication of a normal distribution, thus facilitating prediction of the reproducibility of an average. One may say, with a probability of 95 in 100 of being correct[3], that the true mean of a set of $m$ observations is included in the interval:

$$\bar{P} \pm 2 \frac{\sigma}{\sqrt{m}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

This latter interval is one frequently adopted in experimental work as describing the precision of a set of measurements. The data in Fig. 7 have a standard deviation of 105 psi and the interval $\pm 2 \times 105/\sqrt{19} = \pm 48$ psia is believed to represent the limit of reliability of reported averages. Similar calculations for Area I and II pressure averages lead, respectively, to limits of $\pm 66$ psia and $\pm 98$ psia. There ranges represent relative uncertainties of $\pm 2$ per cent, $\pm 2.6$ per cent, and $\pm 4$ per cent.

From the preceding discussion, it appears that the uncertainties in the average reservoir pressure are dominated by the limitations of attempting to represent the entire reservoir by observations on a small fraction of the sand body. Random instrument errors and weighting error appear to be of secondary importance for data as dispersed as that encountered at Canal. The following would appear to be reasonable estimates of the total uncertainties in the pressure averages used in

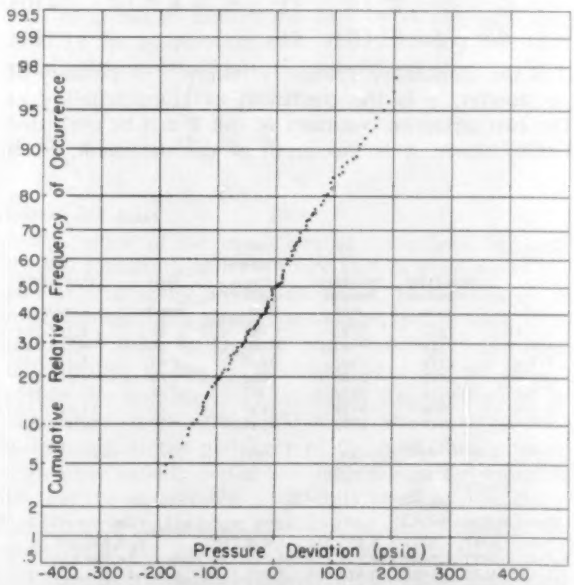


**Fig. 6 — Distribution of observed pressures about the mean.**

*For significance of symbols see "Nomenclature" at end of paper.

this work: reservoir, 2.5 per cent; Area I, 3.1 per cent; Area II, 4.5 per cent.

In order to determine the water inflow from the aquifer surrounding the field, a complete history of the pressure at the original circumference of the field is necessary. Average values for this quantity were obtained from contoured pressure maps by measuring the length of the periphery between isobars and weighting the estimated pressure prevailing in that interval in proportion to the measured arc length. The resulting data were plotted as a function of time and a smooth curve was drawn through the points. The smoothed data are believed reliable to ± 60 psia, or approximately 3.0 per cent.

## Reservoir Material Balance Calculations

Although material balance equations for petroleum reservoirs have been variously expressed in the literature[4,8], it will be expedient for the present work to present a form which will facilitate the direct application of the quantities selected to describe the PVT characteristics of the reservoir fluid.

A volume balance leads to the following equation:

$$(N - n + n_m)(V_L - V_G r) + (Nr_o + g_m + I - g)V_G - NV_{t_o} + q + Q + W = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

It will be assumed that no hydrocarbons migrated across the boundary of the field during any period considered in subsequent calculations. With this quite reasonable restriction, it is possible to set $g_m$ and $n_m$ identically equal to zero when applying the material balance equation to the entire reservoir. $Q$ may be estimated satisfactorily if it is assumed that the aquifer surrounding the field is cylindrical in shape and is sufficiently small that the water in the aquifer responds essentially instantaneously to any pressure disturbance at the original oil-water interface. Then, if $\triangle P_p$ equals the cumulative pressure drop at the periphery of the field, the expansion of the water in the surrounding aquifer will equal $Q$ and will be given by the following expression:

$$Q = \pi fch R_b^2 (R^2 - 1) \triangle P_p = B \triangle P_p \quad . \quad . \quad (10)$$

$$B = \pi fch R_b^2 (R^2 - 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$Q$ is the cumulative volumetric inflow, $f$ is porosity of the aquifer, $c$ is the coefficient of compressibility of The two unknown constants $N$ and $B$ can be evaluated aquifer water, $h$ is the depth of encroachment, $R_b$ is

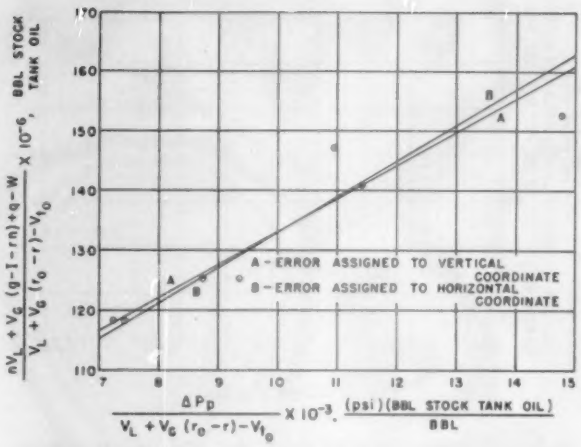


**Fig. 7 — Graphical portrayal of the material balance equation.**

reservoir radius, $R$ is the ratio of the aquifer radius to the field radius, and $P_p$ is pressure at the periphery of the field.

The material balance equation may now be put in the following form:

$$\left[\frac{n V_L + (g - I - rn) V_G + q - W}{V_L + V_G (r_o - r) - V_{t_o}}\right] = N + B\left[\frac{\triangle P_p}{V_L + V_G (r_o - r) - V_{t_o}}\right] \quad . \quad . \quad . \quad . \quad (12)$$

by simultaneous solution of any two equations obtained by independent evaluation of the PVT pressure-production terms in Equation 12. If these two groupings are plotted on graph paper, they should determine a straight line, and furthermore the slope of the line should be equal to $B$ and the intercept should equal $N$.

The production data of interest for the Canal field have been reported in Tables 2 and 3 for the total reservoir and for a breakdown into two arbitrary areas. Calculated values for the expansion of the original connate water in the oil reservoir have also been included. The material balance calculations were not carried beyond 1947 because of the lack of reliable pressure data after that date.

The two production-pressure PVT functions in Equation 12 have been evaluated for seven different time periods from Jan., 1941, through Jan., 1947. The cal-

TABLE 2 — MATERIAL BALANCE CALCULATIONS

| I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Mid-Point Pressure psia | Peripheral Pressure psia | Peripheral Pressure Drop $\triangle P_p$ psi | Time $T$ months | Oil Production $n$ bbl | Gas Production $g$ Mcf | Gas Injection $I$ Mcf | Water Production $q$ bbl | Water Expansion $W$ bbl | Liquid Phase Volume $V_L$ bbl/bbl | Gas Phase Volume $V_G$ bbl/Mcf |
| 1-1-41 | 2562 | 2725 | 840 | 38 | 4,767,288 | 5,130,524 | | 146,863 | 240,038 | 1.4309 | 1.1354 |
| 1-1-42 | 2322 | 2562 | 1009 | 50 | 6,583,181 | 8,567,841 | 412,863 | 244,343 | 298,650 | 1.3881 | 1.2548 |
| 1-1-43 | 2336 | 2305 | 1260 | 62 | 7,643,657 | 10,492,058 | 1,923,326 | 307,416 | 296,460 | 1.3905 | 1.2471 |
| 1-1-44 | 2312 | 2280 | 1285 | 74 | 9,089,395 | 14,641,875 | 5,650,539 | 427,675 | 302,298 | 1.3864 | 1.2603 |
| 1-1-45 | 2218 | 2204 | 1361 | 86 | 10,382,567 | 18,517,182 | 9,737,141 | 532,525 | 325,158 | 1.3703 | 1.3152 |
| 1-1-46 | 2079 | 2128 | 1437 | 98 | 11,623,772 | 25,103,466 | 13,962,156 | 588,669 | 357,504 | 1.3472 | 1.4060 |
| 1-1-47 | 2027 | 2020 | 1545 | 110 | 12,492,883 | 30,062,411 | 17,844,936 | 637,525 | 370,394 | 1.3388 | 1.4435 |

| | XIII | XIV | XV | XVI | XVII | XVIII | XIX | XX | XXI |
|---|---|---|---|---|---|---|---|---|---|
| Date | Gas in Solution $r$ Mcf/bbl | $r_o - r$ Mcf/bbl | $nV_L$ | $g - I - rn$ | $nV_L + V_G(g - I - rn) + q - W$ | $V_L + V_G(r_o - r) - V_{t_o}$ | $\frac{nV_L + V_G(g - I - rn) + q - W}{V_L + V_G(r_o - r) - V_{t_o}}$ | $\frac{\triangle P_p}{V_L + V_G(r_o - r) - V_{t_o}}$ | $Q = B\triangle P_p$ Water Inflow bbl |
| 1-1-41 | .6717 | .0783 | 6,821,512 | 1,948,337 | 8,940,479 | .0568 | $157.40 \times 10^6$ | $14.79 \times 10^3$ | 4,788,000 |
| 1-1-42 | .5992 | .1508 | 9,138,114 | 4,210,336 | 14,366,936 | .1143 | 125.7 | 8.78 | 5,717,000 |
| 1-1-43 | .6033 | .1467 | 10,628,505 | 3,957,314 | 15,574,626 | .1104 | 141.1 | 11.41 | 7,182,000 |
| 1-1-44 | .5962 | .1538 | 12,601,537 | 3,572,239 | 17,229,007 | .1172 | 147.0 | 10.96 | 7,325,000 |
| 1-1-45 | .5690 | .1810 | 14,227,232 | 2,872,360 | 18,212,326 | .1454 | 125.3 | 9.36 | 7,758,000 |
| 1-1-46 | .5298 | .2202 | 15,659,546 | 4,983,036 | 22,896,859 | .1938 | 118.1 | 7.41 | 8,191,000 |
| 1-1-47 | .5155 | .2345 | 16,725,472 | 5,777,394 | 25,332,271 | .2143 | 118.2 | 7.21 | 8,807,000 |

TABLE 3 — CALCULATION OF INTERNAL HYDROCARBON MIGRATION

| I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XIII | XIV | XV | XVI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Pressure psia | $V_L$ bbl/bbl | $V_G$ bbl/Mcf | $r$ Mcf/bbl | $(r_o - r)$ Mcf/bbl | Oil Production $n$ bbl | Gas Production $g$ Mcf | Gas Injection $I$ Mcf | Water Production $q$ bbl | Water Expansion $W$ bbl | Water Inflow $O$ bbl | Recovery Efficiency $n$ $N$ | $N - n$ bbl | $[N(r_o - r) + I - g + nr]$ | Migration $nn(V_L - V_{tr}) + g_m V_G$ bbl |
| Area I | | $N = 38,200,000$ bbl | | | | $NV_{t_o} = 55,900,000$ | | | | | | | | | |
| 1-1-41 | 2540 | 1.4269 | 1.1453 | 0.6649 | .085 | 2,715,688 | 3,045,533 | | 60,270 | 123,891 | 0 | .071 | 35,500,000 | 2.0 | 3,000,000 |
| 1-1-42 | 2307 | 1.3855 | 1.2631 | .5948 | .155 | 3,730,749 | 4,861,315 | 412,863 | 128,371 | 154,142 | 0 | .098 | 34,500,000 | 3.6 | 3,600,000 |
| 1-1-43 | 2379 | 1.3981 | 1.2241 | .6160 | .134 | 4,299,412 | 5,973,964 | 1,923,326 | 157,129 | 153,012 | 0 | .113 | 33,900,000 | 3.7 | 4,000,000 |
| 1-1-44 | 2338 | 1.3909 | 1.2460 | .6039 | .146 | 5,037,344 | 8,718,337 | 5,650,539 | 210,327 | 156,025 | 0 | .132 | 33,200,000 | 5.6 | 2,700,000 |
| 1-1-45 | 2255 | 1.3766 | 1.2930 | .5796 | .170 | 5,670,553 | 11,804,897 | 9,737,141 | 248,968 | 167,823 | 0 | .148 | 32,500,000 | 7.7 | 1,200,000 |
| 1-1-46 | 2101 | 1.3508 | 1.3901 | .5359 | .214 | 6,309,395 | 15,293,328 | 13,962,156 | 272,385 | 184,518 | 0 | .165 | 31,900,000 | 10.3 | − 1,400,000 |
| 1-1-47 | 2018 | 1.3373 | 1.4502 | .5131 | .237 | 6,752,543 | 18,119,787 | 17,844,936 | 296,717 | 191,171 | 0 | .177 | 31,400,000 | 12.2 | − 3,700,000 |
| Area II | | $N = 35,800,000$ bbl | | | | $NV_{t_o} = 52,400,000$ | | | | | | | | | |
| 1-1-41 | 2587 | 1.4355 | 1.1243 | 0.6795 | .070 | 2,051,600 | 2,104,971 | 0 | 86,593 | 116,147 | 4,788,000 | .057 | 33,700,000 | 1.8 | − 2,800,000 |
| 1-1-42 | 2338 | 1.3909 | 1.2460 | .6039 | .146 | 2,582,432 | 3,706,526 | 0 | 115,972 | 144,508 | 5,717,000 | .072 | 33,200,000 | 3.1 | − 3,300,000 |
| 1-1-43 | 2281 | 1.3810 | 1.2779 | .5872 | .143 | 3,344,245 | 4,518,094 | 0 | 150,287 | 143,448 | 7,182,000 | .093 | 32,500,000 | 3.3 | − 3,900,000 |
| 1-1-44 | 2276 | 1.3802 | 1.2808 | .5857 | .164 | 4,052,051 | 5,923,538 | 0 | 217,348 | 146,273 | 7,325,000 | .113 | 31,700,000 | 2.4 | − 1,600,000 |
| 1-1-45 | 2171 | 1.3624 | 1.3445 | .5556 | .194 | 4,712,014 | 6,712,285 | 0 | 283,557 | 157,334 | 7,758,000 | .132 | 31,100,000 | 2.9 | − 1,600,000 |
| 1-1-46 | 2059 | 1.3440 | 1.4202 | .5242 | .226 | 5,314,377 | 9,810,138 | 0 | 316,284 | 172,985 | 8,191,000 | .148 | 30,500,000 | 1.1 | 1,700,000 |
| 1-1-47 | 2036 | 1.3402 | 1.4369 | .5180 | .232 | 5,740,340 | 11,942,624 | 0 | 340,808 | 179,223 | 8,807,000 | .160 | 30,100,000 | −.6 | 4,300,000 |

culations are summarized in Table 2 and are plotted in Fig. 7. It is apparent that there is no unique line through these data. This, of course, does not imply that there are not unique values of $N$ and $B$. The latter quantities certainly exist, but uncertainties in the available data prevent precise evaluation and it is necessary to compromise on some reasonable estimate. This dispersion of data might have been logically anticipated, since both variables involve pressure averages which were previously estimated to contain random uncertainties of several per cent.

These conflicting data were resolved by a normal linear regression analysis based on the tacit assumptions that one of the variables in Fig. 7 is known precisely, that any deviations from the straight line can be assigned to variations in the other variable, and that these variations are described by a normal probability distribution. The assumption of a normal distribution appears plausible, since the dominating uncertainty in both variables is that introduced from the pressure averages, which were found to be approximately normally distributed. The decision in assigning error is not quite as simple. Although van Everdingen, Timmerman, and McMahon[4], in an analysis of the Mercy field, assigned the error to the quantity

$$\left[\frac{n V_L + (g - I - rn) V_G + q - W}{V_L + V_G (r_o - r) - V_{t_o}}\right],$$

it would appear that for the data encountered at Canal there is significantly more uncertainty in the quantity

$$\left[\frac{\Delta P_p}{V_L + V_G (ro - r) - V_{t_o}}\right].$$

The same error is introduced into each by the denominator. The numerator of the first is dominated by uncertainties in average absolute reservoir pressure and the numerator of the latter by average peripheral pressure drop. For the data obtained in Canal field, it was conservatively estimated that uncertainties in average peripheral pressure drop were of the order of three times as large as errors in average absolute reservoir pressure. Using the equations of normal linear regression analysis[3], identical with those of the least squares procedure, solutions for $N$ and $B$ were obtained for both conditions of error assignment, yielding, respectively, values of 77,600,000 bbl and 73,400,000 bbl for $N$. The corresponding lines are shown in Fig. 7. A weighted average value for $N$ of 74 million bbl was accepted as the working answer for the original oil in place. The corresponding value for $B$ was 5,700 bbl/psi.

Again, employing a statistical analysis, confidence regions were computed for $N$ and $B$. The 95 per cent confidence limits are ±17,900,000 bbl and ±1,740 bbl/psi, respectively. Probable errors (50 per cent confidence limits) are ±5,100,000 bbl and ±491 bbl/psi. The confidence bands are of significant width, reflecting the appreciable uncertainties in pressure data. Also, it might be noted that if the pressure readings had been taken twice as frequently, the confidence regions for $N$ and $B$ would have been narrowed only by a factor of approximately 1.4.

Using the value of 74 million bbl of stock tank oil for the original oil in place and the value of 1,463 bbl reservoir volume per barrel stock tank oil for original total volume, the pore volume of the reservoir is computed to be 108 million bbl. This compares with 128 million bbl calculated on the basis of core analysis data. The discrepancy of 15 per cent is considered reasonable in view of the errors inherent in the two methods of computation. The 95 per cent confidence limits for the value of $N$ obtained from material balance calculations corresponds to a range of ±26 million bbl of reservoir volume and hence bracket the value obtained from core data computations.

Using the most probable value of $B$ of 5,700 bbl/psi, a value of 1.75 was calculated for the ratio of the aquifer radius to that of the field by employing Equation 11 in conjunction with the following constants obtained from structural and subsurface data:

$$h = 230 \text{ ft}$$
$$f = 0.22$$
$$R_b^2 = 15{,}250{,}000 \text{ ft}^2$$
$$c = 6.4 \times 10^{-6} \frac{\text{vol/vol}}{\text{psia}}$$

The value of the coefficient of compressibility used for the formation water is twice that of pure water and was arrived at by an approximation to the change in total volume of a natural gas-water system with pressure. The data of Dodson and Standing[6] were used. Incidentally, it can be calculated that for an aquifer of this size and permeability, steady state in the aquifer is reached in less than 200 hours after any pressure disturbance at the periphery of the field, thus substantiating the validity of the assumption used for Equation 10 that the aquifer was sufficiently small to give essentially an instantaneous response to any pressure disturbance at the periphery of the field.

Equation 10 was employed to compute the water inflow from the aquifer. The value of 5,700 bbl/psi for $B$ and the pressure data in Column IV of Table 2

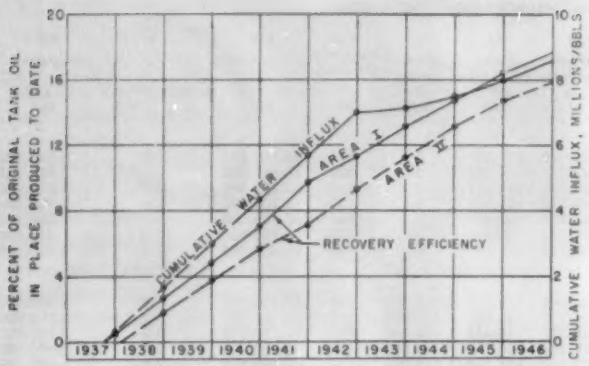


**Fig. 8 — Water influx and recovery efficiency.**

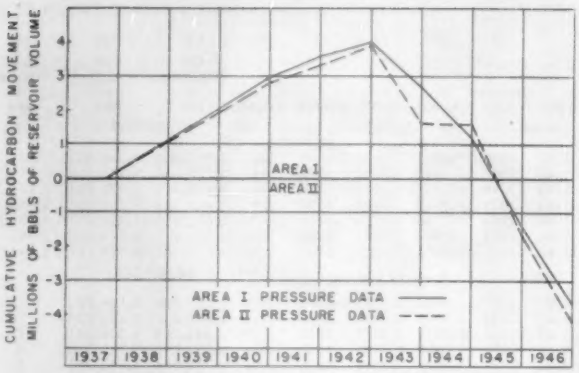


**Fig. 9 — Internal hydrocarbon migration.**

were used. The results are given in Column XXI and are plotted in Fig. 8. Approximately 8,800,000 bbl of water entered the reservoir by Jan., 1947.

## Internal Hydrocarbon Migration

Knowledge of the underground hydrocarbon movement should be informative of the effectiveness of the gas injection program. For this study the field was divided into two sections referred to as "Area I" and "Area II," representing the crestal position and the flanks of the field, respectively. The boundary is indicated in Fig. 1.

The material balance equation may be written in the following form:

$$n_m(V_L - V_G r) + g_m V_G = N V_{t_o} + q - Q - W - (N-n)V_L - [N(r_o - r) + I - g + nr]V_G \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The quantity on the left of this expression represents the reservoir volume of the total cumulative hydrocarbon movement into a portion of the reservoir. The value of $N$ obtained in the study of the entire reservoir was apportioned between the two sections in proportion to the sand volumes. Values of $Q$ obtained above were also used. Two separate portrayals were obtained for the hydrocarbon movement across the Area I-Area II boundary, one by applying Equation 13 to Area I and the second by applying it to Area II. The results are shown in Table 3, and the history of the movement is plotted in Fig. 9. The discrepancy between the two curves is believed to be primarily a reflection of errors in the pressure averages.

These results indicate that approximately 4 million bbl of hydrocarbons (reservoir volume) moved upstructure from the discovery of the field until early 1943. Within a year of the initiation of full-scale gas injection this trend was reversed and, between 1943 and 1947, 8 million bbl of hydrocarbons moved downstructure.

Although some 8 million reservoir bbl of hydrocarbons were moved downstructure in the four years after the full-scale injection was started in the crestal wells, it will be recalled that extensive tests made on selected intervals of wells A44-14 and A25-14 indicated that the movement past these wells was primarily that of gas. Equally indicative are the relative recovery efficiencies of the two areas. The structure at Canal is relatively flat and no large degree of gravity segregation could be reasonably expected. However, that driving force which could be attributed to gravity would tend to move oil downstructure and to enhance the recovery from wells in this sector. Any additional recovery from the partial water drive should benefit the same area. If a gas injection program had not been initiated in the Canal field, it could be reasonably expected, therefore, that the recovery efficiency in the downstructure area would be at least equal to, and probably somewhat better than, that which would be obtained from the upstructure wells. However, production data, Table 3 and Fig. 8, indicate that recoveries from downstructure wells expressed as a fraction of original oil in place have, in general, been appreciably less than that observed from the wells in the higher structural positions. There was no appreciable increase in the relative efficiency subsequent to initiation of gas injection. There remains the possibility that although recovery efficiencies downstructure have shown no significant improvement, oil may nevertheless have been moved into this area and could be recovered if additional wells were drilled at this date.

The available facts are insufficient to support a definite positive or negative statement regarding the nature of the hydrocarbon movement within the reservoir. However, as late as July, 1953, there was no evidence of the formation of a gas cap, and furthermore there have been tangible indications that at least a significant portion of the total migration was simply gas blowthrough. Even if oil has been moved downstructure in appreciable quantities, the ultimate objective still has not been realized, since recovery has not been improved in this area by gas injection upstructure.

The pressure decline curve has been plotted in Fig. 3. The rapid rate of pressure decline observed up to mid-

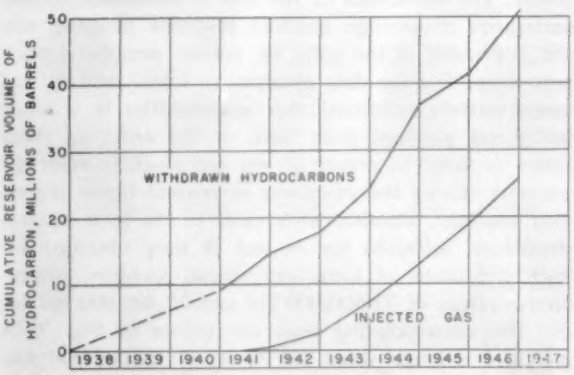


**Fig. 10 — Reservoir volume of injected gas and withdrawn hydrocarbons.**

1941 was, at least, temporarily arrested by the instigation of gas injection. However, by late 1947 the pressure was again rapidly declining. A measure of the adequacy of the amount of gas injected can be obtained by comparing the reservoir volume of the injected gas with the reservoir volume of the cumulative hydrocarbon production. These quantities have been evaluated from the various production and PVT data and are plotted in Fig. 10.

## Summary and Conclusions

1. It was found that PVT data from five samples collected under significantly diverse conditions could be resolved to give an apparently satisfactory portrayal of the volumetric and phase behavior of the reservoir fluid.

2. The errors in pressure averages were found to be dominated by uncertainties introduced by attempting to represent a large reservoir by measurements on only a very small portion. These uncertainties in turn impose the controlling limitations on material balance calculations. The distribution of pressure observations about the mean was found to be approximated by the normal probability distribution.

3. From material balance calculations the most probable value for oil in place was found to be 74 million bbl of stock tank oil. This figure bears an uncertainty of ± 20 per cent. Agreement with the value of 87 million bbl of stock tank oil obtained from core data is regarded as fair.

4. Computations substantiated early indications that water inflow would be of secondary importance in the exploitation of the field. The calculated radius of the aquifer is 1.75 that of the field.

5. There is no evidence of gas cap formation resulting from the gas injection. It appears that the gas injected in the crestal wells has not been effective in increasing recoveries in lower crestal positions. Some 8 million bbl of hydrocarbons were moved downstructure in the 4½ years following the start of full-scale injection, but it appears that at least a significant portion of this migration was gas blowthrough.

6. Capital expenditures and operating costs for pumping units have been reduced by the pressure maintenance provided by the injection gas. This fact, by itself, is considered strong recommendation for maintaining an active injection program.

7. A definite enhancement of recovery was obtained in a small segment of the southern flank of the field by localized gas injection.

## Nomenclature

Restrictions on equations are indicated in brackets following the equation.

**Symbols**

$B$ = a constant, bbl/psi; defined by Equation 11.
$c$ = coefficient of compressibility, vol/(vol) (psi).
$f$ = porosity, a fraction.
$g$ = cumulative gas production, standard Mcf.
$g_m$ = cumulative underground entry of gas, standard Mcf.
$h$ = depth, ft.
$I$ = cumulative gas injection, standard Mcf.
$n$ = cumulative oil production, bbl stock tank oil.
$n_m$ = cumulative underground entry of oil, bbl stock tank oil.
$N$ = original oil in place, bbl stock tank oil.
$P$ = pressure, psia.
$q$ = cumulative water withdrawals, bbl.
$Q$ = cumulative water inflow, bbl.
$r$ = gas in solution, standard Mcf/bbl stock tank oil.
$r_o$ = original gas in solution, standard Mcf/bbl stock tank oil.
$R_e$ = radius of field, ft.
$R$ = ratio of radius of aquifer to radius of field.
$V_G$ = volume of gas phase, bbl/standard Mcf.
$V_L$ = volume of liquid phase, bbl/bbl stock tank oil.
$V_t$ = total volume, bbl/bbl stock tank oil.
$V_{ti}$ = original total volume, bbl/bbl stock tank oil.
$W$ = cumulative expansion of interstitial water, bbl.
$\sigma$ = standard deviation.
$\sigma^2$ = variance.

**Subscripts**

b refers to bubble point pressure.
G refers to gas phase.
L refers to liquid phase.
p refers to peripheral pressure.


## Acknowledgments

The authors thank the management of the Shell Oil Co. for permission to use the data presented. This paper would have been impossible without the thorough and meticulous processing of data by the operating divisions and laboratories of the company.


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★★★

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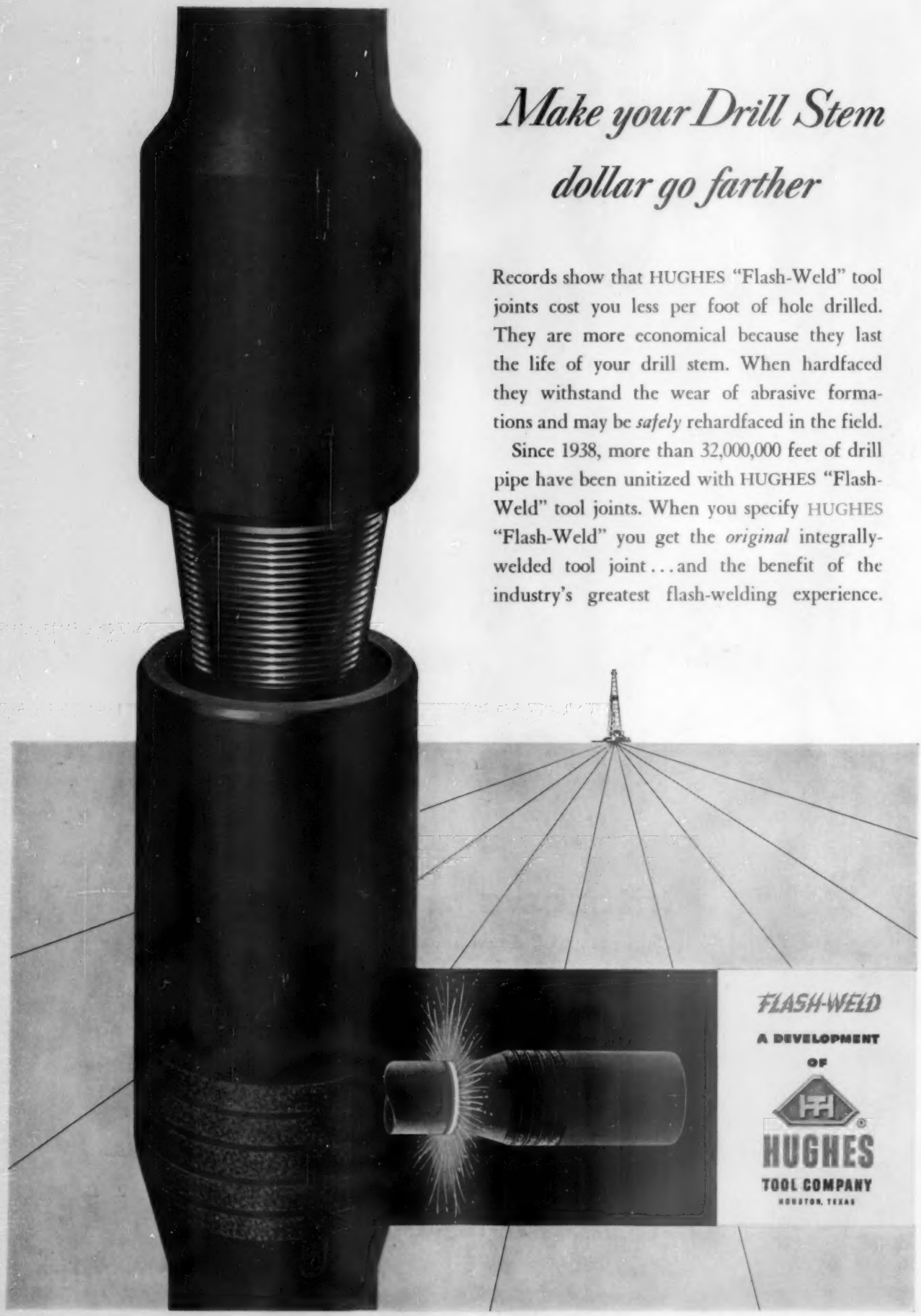


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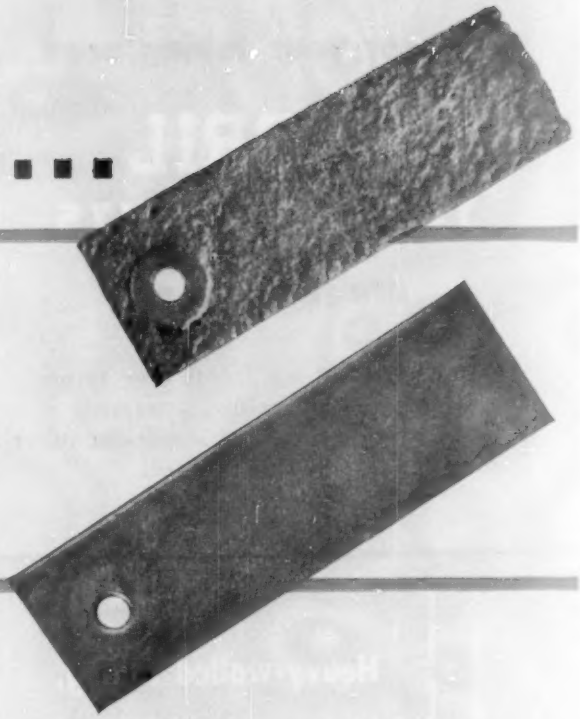

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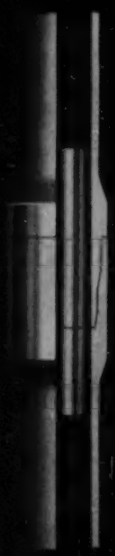

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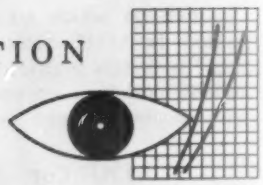

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## NEW HEADQUARTERS BUILDING FOR ENGINEERING SOCIETIES

A problem that has required a great deal of attention from the officers of our Institute during the past two years, as well as those of the other Founder Societies, is the procurement of a new headquarters building for these societies. The four Founder Societies, so named because they were the first national engineering societies founded in this country, are the ASCE (1852), AIME (1871), ASME (1880), and the AIEE (1884). The AiCHE, which was founded in 1908 and which has worked with the other four societies on many projects since, has joined with the Founder Societies in the project of locating a new headquarters.

The Founder Societies now headquarter in what is known as the Engineering Societies Building at 25-30 West 39th Street in New York City. This building was endowed to the Societies by Andrew Carnegie in 1904, erected in 1905-1906, and has since served as their headquarters and that of the Engineers Club of New York. Mr. Carnegie's gift was transmitted in a very interesting way, through the following "laconic but momentous" letter, in his own handwriting:

> *Gentlemen of the Mechanical Engineers, Institute of Mining Engineers, Institute of Electrical Engineers, Engineers Club of New York:*
>
> *It will give me great pleasure to devote, say, one and a half million dollars for the erection of a suitable Union home for you all in New York City. With best wishes.*
>
> *Very truly yours,*
> *(Signed) Andrew Carnegie*

From the Carnegie gift, $1,050,000 was expended for the construction of the Engineering Societies Building, with AIME, ASME, and AIEE each becoming a third owner of the building. In 1917, the ASCE, which had previously established offices elsewhere, joined with the other societies, in contributing $262,500 to the property fund, and three floors were added to the building. In the years since, the four societies have formed a subsidiary corporation known as the United Engineering Trustees (UET), which is now formal owner of the headquarters building.

### Need for New Building

Mr. Carnegie's gift has indeed served these four societies and the engineering profession well. To make a long story short, however, after 50 years of service the building has become obsolete and too small. In 1920 the combined membership of the Founder Societies and AiCHE was some 45,000, and it is now about 160,000. Headquarters employees of the five groups now number some 350. Remodeling and modernizing of the present building seems an unwise expenditure, for an estimated $1,340,000 would be required, and the building would still be inadequate for the societies on a long-range basis.

For the past few years, the Real Estate Committee of the UET has given some preliminary study to the problem of finding a new site and erecting a new building. In 1953 and 1954 other cities began to be interested in the possibility of having the societies move to their environs, and various offers of land and money were received from Chicago, Philadelphia, Pittsburgh, and Washington, D. C. No substantial offer was received

In May, 1954, a Task Committee of the UET Real Estate Committee was formed to study and crystallize the whole problem. This Task Committee, which consisted of several members of the UET and staffs of the various societies, conducted an excellent study of the matter and submitted a comprehensive report in Nov., 1954. The committee considered the following factors as the principal ones influencing the location of the headquarters: availability of manpower for staff and working committee requirements, availability of travel, banking, postal, and printing facilities, and ready sources for supplies and general services. The committee concluded that these requirements could be met in any of the cities making offers, along with New York City, where one or two possible sites were available for purchase.

### Committee of Five Presidents

In late 1954, a committee was formed of the presidents of the five societies concerned, known as the Committee of Five Presidents, which was given the assignment of bringing the matter to conclusion and recommendation. This committee met in Jan., 1955, and concluded that the factors enumerated above were about equal in all the cities under study, and the problem then became one of financing. The offers from Chicago and Philadelphia were very attractive, but the question boiled down to the fact that the most favorable offer came from Pittsburgh with a gift of land and a cash gift of $1,300,000.

Present available assets of the societies from the sale of the present building, a depreciation fund, and a contribution from AiCHE, amount to some $2,500,000. This, combined with the Pittsburgh offer, would permit the erection of a proper building and leave the societies with only $200,000 to be financed, as compared to a remainder of $3,000,000 left to be financed under the sites available in New York City. The Committee of Five Presidents, with the president of the ASCE declining, voted to recommend to the societies that the headquarters be moved to Pittsburgh. This recommendation was then made to the Boards of Directors of the various groups, with the exception of ASCE, in the early part of 1955. AIME President Leo F. Reinartz reported to our Board at the Annual Meeting in Chicago, and the Board postponed a definite decision until its next meeting.

This action definitely brought the matter to a head. Immediately Philadelphia stated that it would meet the offer made by any other city. Various persons and groups interested in keeping the headquarters in New York became active, and indications began to develop that the picture might be decidedly changed in favor of New York. The Committee of Five Presidents took the position that it could not consider offers made subsequent to its decision, because it had established a

(Continued on Page 38)

deadline on which all offers were to have been submitted. In AIME circles at least, there was wide agreement with this position and expressions that the Committee had done an excellent job and taken the only position it could take.

## AIME Consideration of Problem

The AIME Board came to grips with the problem in a meeting on April 13, and devoted almost two hours of discussion to it. Several members of the Board were in favor of moving to Pittsburgh, but others were equally strong in favor of staying in New York. It was apparent that there was a wide division of opinion in the Board, and action was postponed until the next meeting, scheduled for June 15.

During the next two months some significant developments occurred. The AIEE Board had voted to move to Pittsburgh, but the ASCE Board had voted that another study be conducted of the whole question, and that an outside consulting firm be employed for this purpose. The most significant step came with a letter dated June 8, 1955, addressed to the five societies and UET. This letter was signed by 21 prominent individuals, 13 of whom are head of some of the country's largest corporations (General Motors, General Electric, du Pont, Chrysler, I. T. & T.), and eight of whom are heads of educational institutions. This letter was developed largely through the efforts of Mervin J. Kelly, president of Bell Telephone Laboratories, Inc., and it has become known since as the "Kelly letter." Significant statements from it are as follows:

> *"We . . . as members of academic and industrial organizations that are concerned with the welfare of your Societies, . . . are agreed that the fundamental desirability of approaching this matter on a national rather than a local basis transcends our personal preferences.*
>
> *Most industries of the country benefit directly from the technologies included in your organizations. We are sure they will contribute generously to your building funds if your location is chosen on the broad gauged basis suggested (service of the Societies to professions and nation). If such a choice is made, a group of the undersigned will organize a large national committee, . . . to conduct a nationwide drive for funds.*
>
> *"We . . . suggest that . . . an independent management or consulting firm be employed to coordinate . . . these studies, . . . and when the integrated studies are available, that you make your selection on the basis we have suggested. . . . Some of us who are signing this letter will provide the funds to cover the cost (of the proposed study).*
>
> *While we are not now in a position to guarantee the amount of the subscriptions for your building fund, we are confident that the amount required beyond your resources can be raised through a campaign of the scope we have indicated. We assure you that a well organized, diligent and competent effort will be made and continued until the required sum is available, which we understand is approximately $2.5 million."*

## Current Developments

The AIME Board again gave extended consideration to the problem on June 15, and particularly to the proposal made in the Kelly letter. A key point in the discussion was that the proposal offered would place support for the Engineering Center more on a national basis, and this would benefit the entire engineering profession. Again, after almost two hours of discussion, the Board voted by a substantial majority for the AIME to favor the proposal made in the Kelly letter.

The ASME Board took a similar position on June 20, and these two, coupled with the ASCE proposal for a re-examination of the whole question, led the United Engineering Trustees to vote on June 23, 1955:

> *That a Joint Task Committee of 20 members be organized from the five Societies . . . to be charged with the duty of recommending a location for the Engineering Societies Center . . . based upon available data and necessary additional studies . . . to report not later than Jan. 1, 1956. The UET to assume costs for Task Committee . . . but the Task Committee is empowered at its discretion to take advantage of the offer as indicated in the Kelly letter."*

Thus, the whole question has been brought to a definite point of progress. Although there is a time element involved, the question is not one that has to be decided "by midnight of any given day." If the engineering profession will benefit from more extended consideration of the question, and it appears now that it might, then we believe that consideration is justified.

## Petroleum Branch Interest

This whole question has been discussed quite at length at many and various times by Petroleum Branch members. Our Section Delegates to the Annual Meeting, the Branch Executive Committee, Petroleum members of the AIME Board, and numerous individual members have given much thought and consideration to the problem. As might be expected, opinion is somewhat divided. Some feel the headquarters of the Institute would be better located outside of New York City on the assumption that operating costs would be lower; others feel that it should be kept in New York because of the many advantages that city has to offer. We believe the most widely held opinion among Petroleum Branch members is that the headquarters should be located where it can best and most economically serve the various societies and the engineering profession. There has been no organized action, either within the Branch or the Institute, to force a decision for any particular location. When the final vote is taken, it will be up to each member of the AIME Board to cast his personal vote on the basis of the many considerations involved as he sees them.

There has been some discussion to the effect that the new Engineering Center should be expanded to take in all interested engineering societies, rather than the five involved so far. This would seem to have some desirable aspects; and if funds for the center are raised on a national scale, steps in this direction will probably be taken. We do not anticipate that the Petroleum Branch headquarters will be moved from its present location in Dallas.

Although the new Task Committee is to report by next Jan. 1, it seems safe to predict that the basic question of where to locate the Engineering Center will not be decided for perhaps a year, and it will then be some time before it is erected and in operation. We believe this is proper, however, for if the time taken for this step finally serves to weld the engineering profession more closely together and to raise its stature, it will be time well spent indeed. ★★★

# PERSONALS

STANLEY G. BENDORF has opened an office in the Fidelity Union Life Building, Dallas, as an independent petroleum consultant. He is specializing in analyses of data pertaining to search for and production of oil and gas and in making evaluations of existing petroleum properties. Bendorf recently resigned from the firm of DeGolyer and MacNaughton. His 15 years' experience in the industry also includes service with Cities Service Gas Co. and Phillips Petroleum Co. He is a geology and petroleum engineering graduate of Wisconsin Mining School and Missouri School of Mining and Metallurgy.

W. P. SCHULTZ (left) and NORMAN J. CLARK have joined the Engineering and Consulting Dept. of Core Laboratories, Inc., Dallas. Schultz, a chemical engineering graduate of Rice Institute, was with Humble Oil and Refining Co. from 1947 until accepting this position with Core. With Humble he studied processing plant design and instructed engineers and supervisors in reservoir engineering. Clark was supervisory reservoir engineer for Humble, and he assumes the job of assistant manager of the Engineering and Consulting Dept. He is a graduate of Southwest State Teachers College and the University of Oklahoma. His duties at Humble included reservoir engineering studies, training of reservoir engineers, and coordination between the company's research and petroleum engineering departments.

J. P. GARTEN, former drilling engineer for the Long Beach (Calif.) Oil Development Co., has joined the petroleum department of the Chase Manhattan Bank, New York City. He was chairman of the Junior Petroleum Group in 1954 and membership chairman of the newly-formed Southern California Petroleum Section for 1955.

MAURICE E. HANSON has been transferred from Wichita to Houston to act as service supervisor for Dowell Incorporated. Since joining the company in 1945, he has worked steadily up to area manager in the Kansas district. In his new position Hanson will be responsible for the coordination and supervision of Dowell's various oil field services in the Texas Gulf Coast district. He is a graduate of Kansas State College.

*(Continued on Page 47)*

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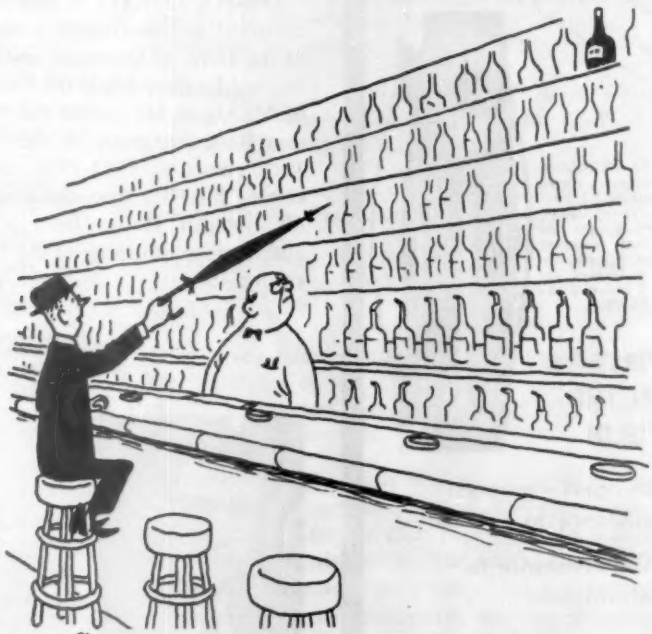

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# MEET the AUTHORS

RIKI KOBAYASHI is professor of chemical engineering at Rice Institute, Houston. He holds a BS degree from Rice and a PhD degree from the University of Michigan in chemical engineering. Formerly he was associated with the Continental Oil Co.

DONALD L. KATZ is professor of chemical engineering and chairman of the Dept. of Chemical and Metallurgical Engineering at the University of Michigan. He started the Production Research group at the Phillips Petroleum Co., 1933-1936, after receiving his PhD from the University of Michigan. He has been an active author since returning to the University in 1936.

T. D. MUELLER is a research engineer in the Oil Field Research Div. of Cal Research where he is working in the field of applying high speed digital computers to the solution of problems of oil production. He holds a BS in chemical engineering from University of Michigan and MS in petroleum engineering from the University of Southern California.

J. EARL WARREN is an associate research engineer in Oil Field Research Div. of California Research Corp. at La Habra, Calif. He is a graduate of the University of California and holds a BS degree in electrical engineering.



W. J. WEST is supervisor of the reservoir and well production analysis section at California Research Corp. He holds a BS degree in physics from MIT (1944) and a PhD degree from California Tech (1949). From 1944 until 1946 he was a staff member of the Radiation Laboratory. In 1948 he joined the Oil Field Research Div. of Cal Research.

J. M. EDWARDS is a geologist and radiation logging research engineer for McCullough Tool Co. The 1952 graduate of the University of Southern California formerly worked for Union Oil Co. of California. He is now studying for his MS degree in geology at the University of Southern California.

*(Continued on Page 48)*

**October 27-28, 1955**

# FORMATION EVALUATION SYMPOSIUM TO BE HELD in HOUSTON

A Formation Evaluation Symposium will be held on Oct. 27-28 at the University of Houston. Sponsors of the meeting are the Gulf Coast Section of AIME, and the University of Houston Student Chapter of AIME and Dept. of Petroleum Engineering.

Fourteen papers are scheduled for presentation at the Symposium. Eight will be presented the first day and six the second. There will be an equipment display of formation evaluation equipment throughout the two-day symposium period.

## TENTATIVE PROGRAM

*(Both Papers and Speakers are Tentative)*

### THURSDAY, OCT. 27

*Fundamental Problems in Formation Evaluation* by Norman J. Clark, Core Laboratories, Inc.

*Subject Content:* The development of the total problem of formation evaluation. The significance and interdependence of the parameters obtained from each of the methods. Recommendations for an optimum program. Prediction of future areas of investigation.

*Fundamental Theory and Instrumentation of Electric Logging* by I. L. Roberts, Schlumberger Well Surveying Corp.

*Subject Content:* Discussion of electrode spacing, method of recording, and curve limitations of standard logs with demonstration of each point by illustration of actual log. Special logging devices. Prediction of future developments.

*Fundamentals of Quantitative Analysis of Electric Log Interpretation* by R. H. Winn, Halliburton Oil Well Cementing Co.

*Subject Content:* A basic fundamental coverage. All limitations emphasized but the potential of quantitative analysis stressed. Specific, careful, and illustrated definitions of all terms used. The best source of information for each term introduced. Prediction of future development of quantitative logging application.

*Electric Logging in Shaly Sands* by M. P. Tixier, Schlumberger Well Surveying Corp.

*Subject Content:* General and specific treatment of shaly sands.

*Fundamental Theory and Instrumentation of Radioactivity Logging* by John E. Sherborne, Union Oil Co. of California

*Subject Content:* Complete development of the theory and instrumentation of the gamma ray and all types of neutron radioactivity recordings.

*Mud Analysis Logging* by R. W. Wilson, Baroid Sales Div.

*Subject Content:* Complete explanation of all recordings, technique for obtaining readings, specific applications and limitations. Case histories where applicable of both successful and unsuccessful applications. Recommendations for an optimum program.

*Core Analysis* by Ben Elmdahl, Core Laboratories, Inc.

*Subject Content:* Precautions to be observed when taking a core. Analysis of fluid content and physical properties in regard to technique, significance of parameters, and limitations. Specific problems and application by areas.

*Drill Stem Techniques and Analysis* by Marshall Black, Humble Oil and Refining Co.

*Subject Content:* Fundamentals of testing. Specific mechanics of the technique by areas. Test results and chart analysis by areas.

### FRIDAY, OCT. 28

In papers to be presented on the second day of the meeting the Symposium Committee has asked the authors to include: (a) an overall evaluation coverage including methods other than logging; (b) where possible, the evaluation technique responsible for the decision to set pipe; (c) where applicable, the reliability of the physical parameters such as porosity, water saturation, etc., for use in reservoir analysis; (d) the drilling fluid program; (e) the coring program; (f) the testing program; (g) indication of other geological areas similar to the one specifically covered by the paper; and (h) a recommended formation evaluation program for the area covered.

*Quantitative Interpretation of Electrical and Radioactivity Logs in Felix Jackson #40 Well, Oyster Bayou Field, Chambers County, Texas* by C. R. Glanville, Sun Oil Co.

*Interpretation of Electrical Logs: La Gloria and Seeligson Fields, Brooks and Jim Wells Counties, Texas*, by speaker to be selected.

*Evaluation of Logs Run in San Andres Formation, Adair Pool, Terry County, Texas* by E. E. Finklea, Amerada Petroleum Co.

*Electrical Logging in the Quinduno Field* by J. D. Owens, Phillips Petroleum Co.

(Tentative) Subject Matter: A complete formation evaluation study of the Wilcox Formation by S. M. Paine, Shell Oil Co.

(Tentative) Subject Matter: An integrated summary of the highlights of the subject matter contained in each of the five papers listed above by C. V. Kirkpatrick, University of Houston.

Papers will be given in the Ezekiel Cullen Auditorium, which has a seating capacity of 1,800. Presentation time will be 25 minutes for each paper, and 15 minutes will be allowed for discussion. The exhibit area will be in the parking lot immediately east of the auditorium.

The organization committee for the Symposium is composed of: J. D. Clark, Union Oil Co. of California, general chairman; C. B. Scotty, The Texas Co.; J. W. Walker, Shell Oil Co.; Johnny Shearin, Core Laboratories, Inc.; T. O. Allen, Humble Oil & Refining Co.; and C. V. Kirkpatrick, University of Houston.

Committee chairman are: C. V. Kirkpatrick, program; L. B. Lipson, University of Houston, arrangements; H. M. Krause, Humble, and Guy H. Johnston, consulting engineer, registration; R. R. Rieke, Schlumberger, publicity; George R. Gray, Baroid, publication; R. E. Bush, Lane Wells Co., exhibits; and T. O. Allen, Humble, advisory. ★★★

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## AUTHORS

*(Continued from Page 40)*

A. L. SIMPSON holds BS and MS degrees from the University of Southern California, having received his MS in February of 1955. In 1951-52 he was a teaching assistant at USC and held a marine geology research fellowship with Allen Hancock Foundation. His present position is geologist and radiation logging research engineer for McCullough Tool Co.

JOHN J. ARPS is vice-president in charge of the Economics and Evaluation Dept. of The British-American Oil Producing Co., Dallas. The native of the Netherlands was graduated from Technical University of Delft, Holland, in 1932. He worked in Eastern Europe, the Far East, and South America before joining British-American in 1940 as district engineer in their Gulf Coast Area.

T. G. ROBERTS has been a petroleum engineer in British-American's Economics and Evaluation Dept. for the past two years. The 1950 University of Oklahoma graduate worked for British American in the summers of 1948 and 1949 and for a year following graduation, until he was called into the military service in 1951.

## Kansas Section Pays Dues For Winner of Contest

The Kansas Local Section has honored the University of Kansas student who won first place in the Undergraduate Div. at the AIME Mid-Continent Section Student Paper Contest. They have paid the first year AIME Junior Membership dues for Edward Arnold Freeburg.

The Section recognized Freeburg's achievement at a recent meeting by presenting him with a Special Student Achievement Award and a Junior Membership pin. Freeburg's paper, "A Neophyte Views Price Regulations," is now being considered in the All-AIME Student Paper Contest.

He was graduated cum laude in petroleum engineering from the University of Kansas this spring. A native of McPherson, Kan., he came to the University on the Summerfield Scholarship, the highest scholastic award available there.

## OFFICER NOMINEES for 1956 DECLARED ELECTED

The previously-announced nominees for 1956 Petroleum Branch officers have been declared elected. No additional nominations were made to those presented by the Branch Nominating Committee by the deadline of Aug. 15; therefore, balloting by the membership was not necessary.

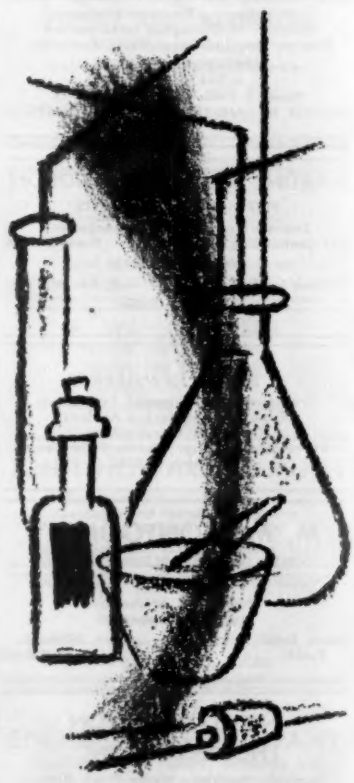
T. C. Frick of The Atlantic Refining Co., Dallas, will be Petroleum Branch chairman. R. C. Earlougher, Tulsa petroleum consultant, and T. A. Atkinson, Douglas Oil Co., Paramount, Calif., will be vice-chairmen. H. N. Lyle, Renwar Oil Co., San Antonio, and Gordon H. Fisher, Plymouth Oil Co., Sinton, Tex., will begin three-year terms on the Petroleum Branch Executive Committee.

The newly-elected officers are to be installed in Feb., 1956. Their biographical sketches were published in the May, 1955, issue of JOURNAL OF PETROLEUM TECHNOLOGY, along with a request for additional nominations.

## College Grants Planned By Dowell Incorporated

Dowell Incorporated has announced the establishment of seven scholarships and two fellowships in the fields of engineering and chemistry totaling $7,500 annually. The first awards will be available for the 1955 school year.

The scholarships, providing $500 for a senior student in Petroleum or Geological Engineering, have been awarded for the 1955 academic year to Oklahoma A. & M., University of Oklahoma, Kansas State, University of Kansas, University of Texas, Louisiana State and Colorado School of Mines. Graduate fellowships in Chemistry for the same period were announced for Kansas State and University of Texas. These provide $1,500, for the student and $500 to the University for equipment and supplies used by the fellowship student. Selection of the students for both the scholarships and fellowships will be made by the college deans and the professors in charge of the departments from which the students are chosen.

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## "AIME Membership Award" to Be Given for Securing New Members

An individual AIME Membership Award will be given this year to each member who secures five or more new applications for membership.

The award is a lapel button consisting of the AIME blue and gold emblem, surrounded by a white enamel border with the words "Membership Award" in gold letters. From the button hangs a pendant with a numeral "5" or "10" indicating the number of applications secured.

A member should print the words "Credit to ....," with his full name, in ink at the top of each application he obtains. The number of applications credited to each individual will be recorded at Institute headquarters. When a member has five applications to his credit, the pin will be sent to his local section for presentation at its next meeting. Successive awards will be given in multiples of five, with the appropriate pendant attached.

## ALUMNI REUNION PLANNED

The second Alumni Reunion of the Minnesota School of Mines and Metallurgy will be held Friday, Oct. 21, 1955. A technical session, banquet and dance, and the Michigan-Minnesota football game will be highlights of the meeting. Make reservations by contacting R. L. Dowell, 306 Appleby Hall, Minneapolis 14, Minn.

## Reprints of Faith of Engineer

Reprints for framing of "Faith of the Engineer," published on the June JOURNAL OF PETROLEUM TECHNOLOGY cover, are still available. They are printed on parchment-colored mat paper and will be sent to any member free of charge upon request.

## Necrology

| Date Elected | Name | Date of Death |
|---|---|---|
| 1952 | Rosenkranz, Ronald | June 13, 1955 |
| 1919 | Stathers, Silas C. | April 29, 1955 |

**Regular Meetings Started by**

# NEW VENEZUELA LOCAL SECTION ELECTS OFFICERS

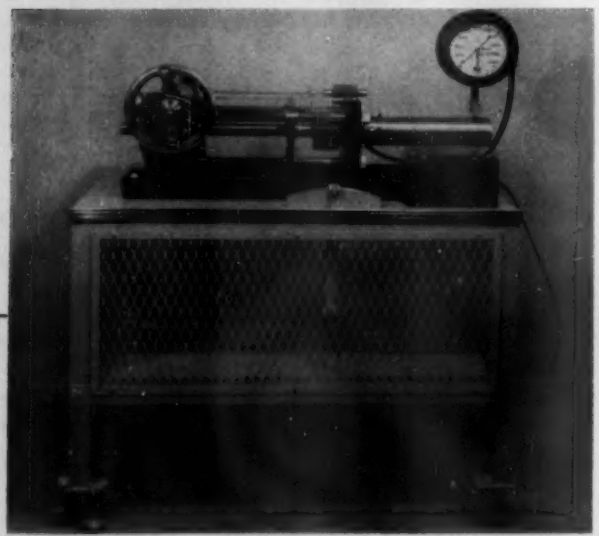
The Venezuela Local Section has elected officers and is now holding monthly meetings. The establishment of this local section was authorized last December by the AIME Board of Directors.

Pictured on the right are the officers of this section. On the front row, left to right, are: Jose Paez, Socony-Vacuum Oil Co., first vice-chairman, and C. F. Rust, Socony-Vacuum Oil Co., secretary. Left to right on the back row are: Don M. Chase, Mene Grande Oil Co., chairman; John Feeser, A-Z Export, second vice-chairman; and M. W. Breedlove, Las Parceles de Anaco, treasurer.

The May meeting, held at Chepa's Icehouse at Anaco, featured a talk by T. A. Pollard, of Magnolia Petroleum Co., Dallas. He spoke on "In-Situ Combustion," explaining his company's recent research efforts in the laboratory and field on this form of secondary recovery. As treasurer of the Petroleum Branch and a member of the Executive Committee, Pollard also welcomed the new section into the AIME.

The meeting (pictured on right) was attended by 70 members and guests. Every company in the area was represented, with some engineers making overnight trips from distant points to attend.

Chairman Don M. Chase would like to have several programs each year featuring speakers from the United States who are in Venezuela on business. He has requested that AIME members contact him should they plan to be in that area and be willing to make a talk.



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Your reporting to us any change of address or title is necessary if we are to be accurate. The form below is provided for your convenience and should be sent to Petroleum Branch AIME. 800 Fidelity Union Bldg., Dallas 1, Tex.

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Material for the "Personals" page published in JOURNAL OF PETROLEUM TECHNOLOGY is taken from additional information provided. Should you wish to let your friends in AIME know of a recent change, attach a sheet giving your former position, your new position, and other information suitable for a "Personals" notice.

**One month normally required for change of address.**

# PERSONALS

*(Continued from Page 39)*

GEORGE L. GORE has been promoted from petroleum engineer to district engineer for Dowell, Inc., at Denver. He joined the company in 1949 after receiving an electrical engineering degree from Oklahoma A&M. Prior to transfer to the Denver office in Aug., 1954, he had served in various capacities at Great Bend, Kan., and Tulsa.

ROBERT R. WALLACE has been transferred to Dallas by Seaboard Oil Co. His move from Corpus Christi necessitated his resignation as chairman of the Southwest Texas Local Section. For the remainder of Wallace's term RALPH E. WARNER of Forest Oil Corp., San Antonio, will serve as chairman, and CHESTER L. WHELESS of LaGloria Oil and Gas Co., Corpus Christi, will act as administrative director of the section's executive committee.

FREDERICK ARTHUR JOHNSON (right) receives a memorial certificate on the fortieth anniversary of his graduation from the University of Pittsburgh with a degree in petroleum engineering. H. G. BOTSET, head of the University of Pittsburgh Dept. of Petroleum Engineering, is shown making the award. In 1915 Johnson was the first man in history to receive a petroleum engineering degree. The presentation was made to the Oil City, Pa., consultant in conjunction with the annual meeting of the Pennsylvania Grade Crude Oil Association in Pittsburgh.

M. T. HIGGS has resigned his position as director and field operations vice-president of Lane-Wells Co., one of the Dresser Industries. He had joined Lane-Wells in 1938 and was manager of the Gulf Coast Div. before being transferred to the Los Angeles head office in 1947. In 1950 he was made a director of the company, and in 1952 he became vice-president. His future plans were not announced at the time of his resignation.

A. W. WALKER has resigned as head of the Dept. of Petroleum Engineering at the University of Tulsa because of poor health. He will continue as a part-time professor in petroleum engineering there and as chairman of the Petroleum Branch Education Committee. ★★★


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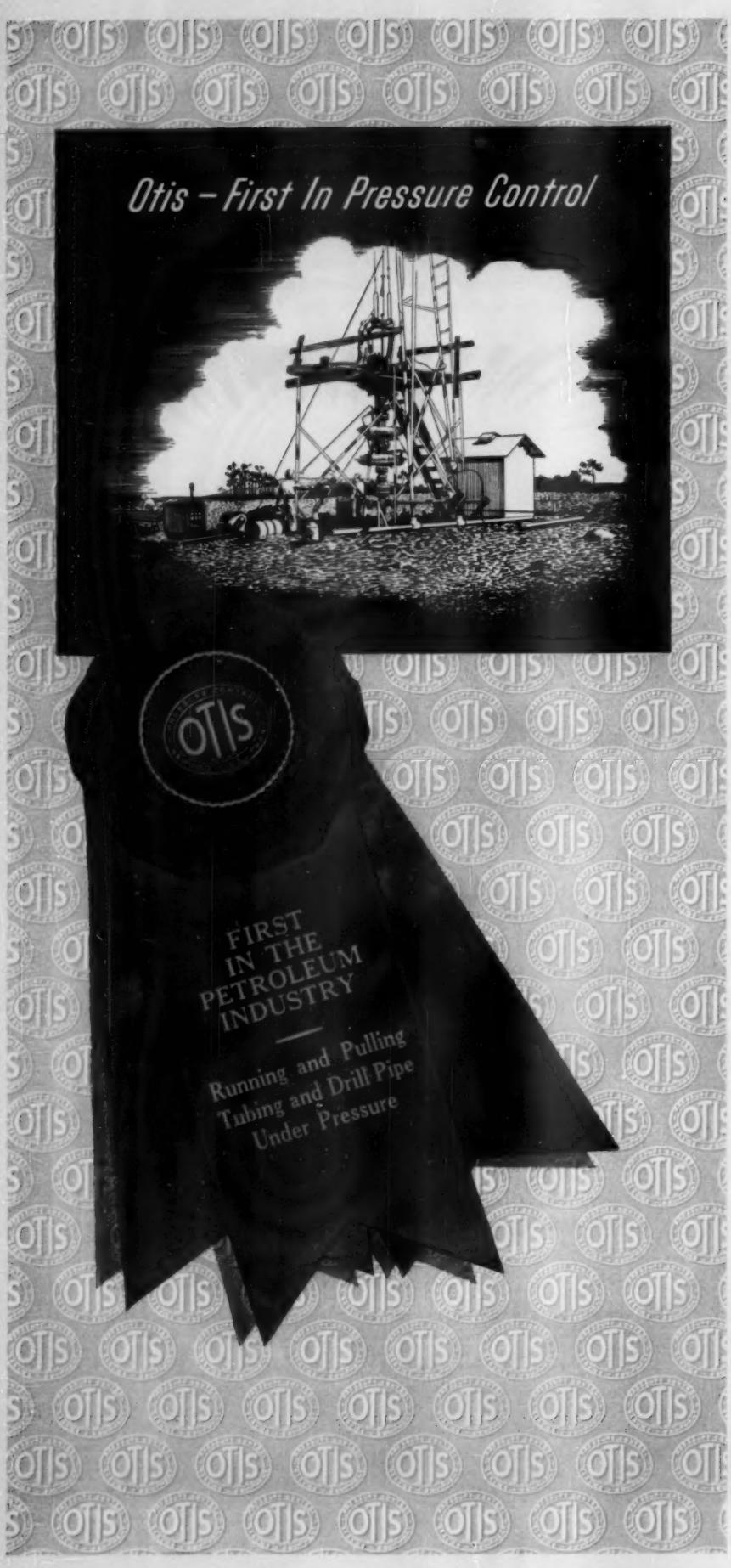


The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, Address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1. These replies will be forwarded unopened and no fees are involved.

## PERSONNEL AVAILABLE

☆ Petroleum and Geological Engineer desires a change in positions. Recent graduate with summer experience in oilfield work during school vacation. Now engaged in waterflooding work. Married. Code 254.

☆ Petroleum Engineer, 33, with five years' experience in production and reservoir engineering seeks position with independent in Southwest area. Now employed by major company, married, one child. Code 252.

☆ Petroleum Engineer with six years' intensive experience in Arkansas, Louisiana, and Texas, desires position with opportunity for advancement. Graduate of 1949, married, two children. Now employed, and responsible for drilling, workovers, production, and waterflood project for independent. Code 256.

☆ Graduate Petroleum Engineer, age 32, married. Ten years' extensive experience in rotary and cable tool drilling, primary and secondary recovery production techniques, and administrative work for major and independent firms. Desires a responsible position anywhere in Continental North America with an aggressive organization. All offers acknowledged. Code 257.

☆ Registered Chemical Engineer, 43, married, two children. Ten years in drilling mud and fluid flow research. Background of physical metallurgy and physical and non-destructive testing and inspection. Looking for an opportunity to combine oilfield, research, and metallurgical experience. West Coast preferred. Now employed. Code 258.

☆ Experienced waterflood engineer capable of evaluating, developing, and managing flood properties desires position with aggressive independent. Has Oklahoma professional engineer registration. Code 259.

☆ Reservoir Engineer and Logging Expert, 35, married, with seven years' experience in field engineering and all phases of reservoir engineering with one major company. Currently employed as reservoir engineer in a key position. Desires responsible staff position with opportunity for advancement. Code 261.

POSITIONS OPEN

☆ **Several positions are currently available in petroleum engineering departments of colleges and universities. Included among these are positions in two institutions as head of the petroleum engineering department. Any member wishing further information on these openings should contact Joe B. Alford, Executive Secretary of the Petroleum Branch, 800 Fidelity Union Building, Dallas.**

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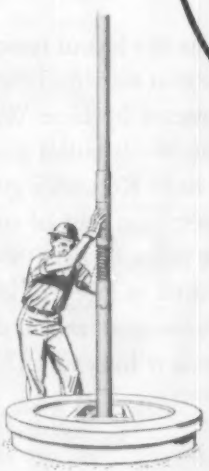

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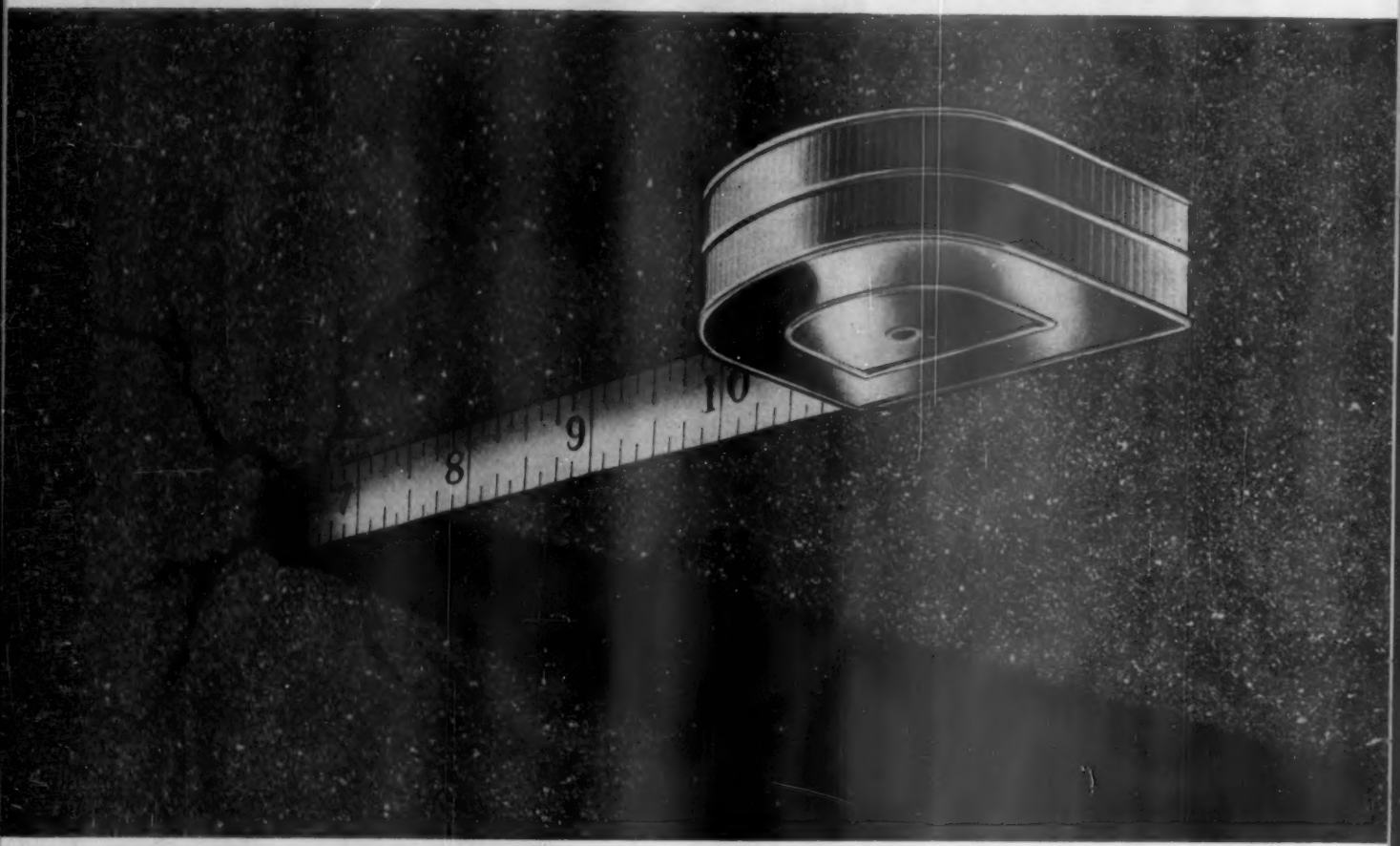


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TECHNICAL NOTE 294

# METASTABLE EQUILIBRIUM in the DEW POINT DETERMINATION of NATURAL GASES in the HYDRATE REGION

RIKI KOBAYASHI
JUNIOR MEMBER AIME
THE RICE INSTITUTE
HOUSTON, TEX.

DONALD L. KATZ
MEMBER AIME
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICH.

## INTRODUCTION

The dew point of natural gas which has been in equilibrium with gas hydrates has been reported to be lower than that obtained for natural gas in equilibrium with water[1,2]. Hammerschmidt[1] reports a lowering of the dew point of 13° F for a natural gas in equilibrium with hydrate at 38° F and 525 psi. Records and Seely[2] likewise show that the dew point of gas leaving hydrate separators[3] is as much as 15° F below the separator temperature.

This paper presents the reasons for the observed differences between the equilibrium temperatures and the dew point temperatures. Descriptions of the dew point determination by the Bureau of Mines and ASTM tester[3] indicate that the dew point is taken as the temperature at which liquid water droplets first begin to appear on the cooled mirror surface even though the temperatures involved are below that required for the formation of gas hydrates or ice.

## PRESSURE-TEMPERATURE DIAGRAM FOR METHANE-WATER SYSTEM

Fig. 1 presents a schematic pressure-temperature diagram for the methane-water system[5] for some constant pressure between the critical pressures of pure methane and pure water i.e., pressures frequently encountered in pipeline operations. The possible equilibrium relations are shown by the heavy solid lines. Curve AE represents the saturated water content or dew point of gas in equilibrium with a water-rich liquid solution while curve EF represents the dew point of gas in equilibrium with hydrates. In addition the dotted line DE labelled "metastable dew point" is introduced to explain the apparent discrepancy between the dew point determination and gas-hydrate equilibria. Thermodynamics place certain restrictions on the location of line DE[6], namely, that (1) the concentration of water along the line DE be greater than the concentration of water along EF or that the metastable line split the angle formed by the intersection of line GE and EF

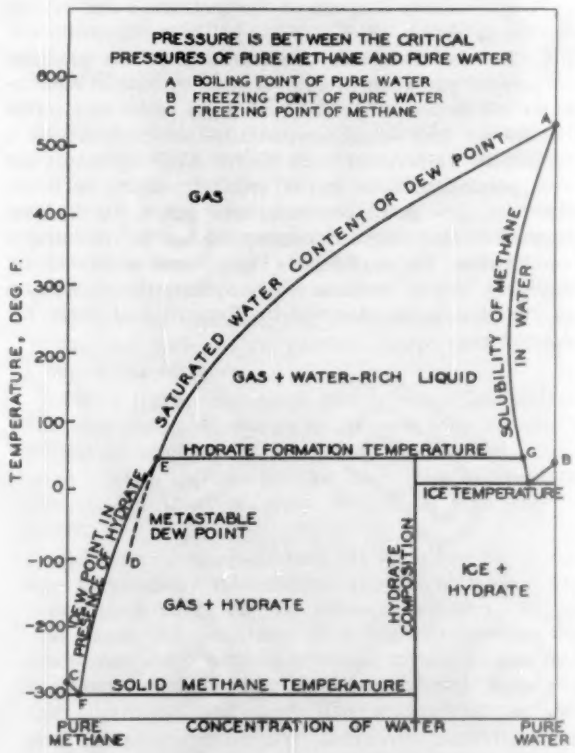


FIG. 1 — SCHEMATIC TEMPERATURE-COMPOSITION DIAGRAM FOR METHANE-WATER SYSTEM.

Original manuscript received in Petroleum Branch office on Dec. 13, 1954. Revised manuscript received on June 30, 1955.
[1]References given at end of paper.

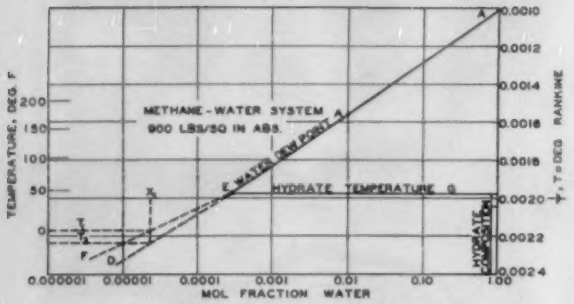


FIG. 2 — TEMPERATURE COMPOSITION DIAGRAM OF METHANE-WATER SYSTEM AT 900 PSI.

and (2) that line DE be a smooth extension of line AE. Although the section shown in Fig. 1 is for the methane-water system, a similar one could be drawn for ethane-water or propane water. A lean natural gas would be expected to approach the behavior described for the methane-water system. Corresponding to extension DE of line AE there should exist a metastable extension of line AG, which is not shown.

At temperatures below line GE, at the pressure for which the phase diagram is drawn, vapor and hydrate are in equilibrium along EF when methane is in excess of the theoretical amount required to form the hydrate.

The existence of liquid water on the mirror of the dew point tester below EG where gas and hydrate are in equilibrium and the reproducibility of the dew point require a metastable equilibrium.

## QUANTITATIVE DIAGRAM

A quantitative diagram of the methane-water system has been drawn at 900 psi, Fig. 2, to illustrate the difference in the water concentration of the methane or natural gas when in contact with hydrate at equilibrium and in contact with liquid water under metastable conditions. The actual temperatures are indicated on a reciprocal temperature scale. Curve AED represents the dew point conditions at 900 psia[4]. It should be noted that the dew point concentrations below the hydrate formations temperature correspond to the metastable equilibrium. Curve EF of Fig. 2 was obtained by applying to the methane-water system the depression of the dew point observed by Records and Seely for natural gas.

Consider the process of contacting a gas in equilibrium with hydrate at temperature $T_1$ followed by a dew point determination. The water content of the equilibrium vapor at $T_1$ (0°F) is $x_1$, (.000024 mole fraction) from the hydrate-vapor equilibrium curve. This water content, $x_1$, is present in the gas which shows a dew point of $T_2$ (−15°F). For the metastable equilibrium curve DE, $T_2$, the water dew point would be lower than $T_1$, the equilibrium hydrate temperature.

## CONCLUSIONS

It should be noted that charts which give the equilibrium water content of natural gases as a function of temperature and pressure[5,6] are for liquid water-gas equilibria, including the metastable equilibrium when such occurs. Hammerschmidt[1] calculated the fugacity of water over hydrate but no other relationship has been presented to show the water content of gases in equilibrium with hydrate. Such data along with the water content charts of natural gas in equilibrium with liquid water would give a quantitative verification of the metastable relationship described.

## ACKNOWLEDGMENT

Acknowledgment is made of the contribution of Professor L. O. Case to the phase rule analysis of this problem.

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1. Hammerschmidt, E. G.: "Formation of Gas Hydrates in Natural Gas Transmission Lines," *Ind. Eng. Chem.* (1934) **26,** 851.
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AIME

PETROLEUM TRANSACTIONS

# The EFFECT of the RELATIVE PERMEABILITY RATIO, the OIL GRAVITY, and the SOLUTION GAS-OIL RATIO on the PRIMARY RECOVERY from a DEPLETION TYPE RESERVOIR

J. J. ARPS
*MEMBER AIME*
T. G. ROBERTS
*JUNIOR MEMBER AIME*

*BRITISH-AMERICAN OIL PRODUCING CO.*
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T. P. 4103

## INTRODUCTION

Since the introduction of the relative permeability concept in the middle thirties[1,2] various investigators have shown[3,10,11,14,33] how the basic equations for the flow of oil and gas through porous media can be utilized to compute the recovery from depletion type or solution gas drive type reservoirs under certain conditions, when the necessary physical data pertaining to the reservoir rock and its reservoir fluids are known.

In the study by Muskat and Taylor[34] in 1945, the effects of viscosity, gas solubility, shrinkage, and the permeability-saturation characteristics of the producing formation on the production histories and the recovery of gas drive reservoirs were analyzed. Each parameter was varied a limited number of times, while keeping the others constant. The work was not carried to the point where the data could be used directly to estimate the primary recovery in those cases where certain rock and fluid characteristics were known or could be assumed.

Since the publication of this classic study, the work by Beal in 1946[16] and Standing in 1952[18] has established general correlations of oil viscosity and shrinkage with gas solubility and oil gravity. In addition, a considerable number of relative permeability relationships for different types of reservoir rocks has been published[2,5,6,12,17,19,20]. Also, the burden of the numerical work required in the solutions of the differential equation has, during the last few years, been greatly reduced with the availability of modern electronic computing facilities.

The purpose of this paper is therefore to present the results of a large number of such recovery computations covering the normal range of variation of the main parameters such as the type of rock, the API gravity of the oil, and the amount of gas in solution.

As is to be expected, the ultimate recovery is found to increase with the oil gravity, except for the higher solution gas-oil ratios.

Within the normal range of solubilities, the ultimate recovery generally appears to decrease with the amount of gas in solution for the higher oil gravities, and to show a slight increase for the lower oil gravities. Intermediate oil gravities seem to fall between the two trends.

The type of reservoir rock, as identified by its relative permeability relationship, appears to have a very pronounced effect on the ultimate recovery. In general, sands and sandstones show higher recoveries than limestones and dolomites, although certain intergranular limestones seem to show a higher theoretical recovery than unconsolidated sand. The recovery from sands and sandstones generally decreases with increasing cementation and consolidation, while the recoveries from limestones and dolomites are highest for the intergranular type and lowest for the fracture type porosity.

Paper presented at AIME Annual Meeting in Chicago Feb. 13-17, 1955. Original manuscript received in Petroleum Branch office on Dec. 30, 1954. Revised manuscript received July 7, 1955.

[1]References given at end of paper.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1955, should be in the form of a new paper.

## STATEMENT OF THE PROBLEM

Reservoirs of the depletion type which lack the aid of a natural water influx, due to low permeability or absence of an aquifer, generally show disappointingly low recoveries by primary means, of the order of only 10 to 30 per cent of the oil in place. This low recovery efficiency presents a challenge to the reservoir engineer. Most of the newer depletion type fields—which are of sufficient size and where stimulation of the natural forces by fluid injection is economically feasible—are therefore rarely left alone to be depleted by their natural primary mechanism.

Since recommendations for fluid injection programs always need economic justification, and since the same reservoir cannot be produced more than once, a thorough understanding of the factors contributing to the primary recovery without fluid injection is of vital importance. To cover all possible variables which could enter the picture in a general study such as this would be impractical. It is the purpose of this paper, therefore, to study the effect of the most important variables on the ultimate recovery while keeping those of lesser significance constant.

The most important variable appears to be the type of reservoir rock as identified by its relative permeability relationship. By selecting six different curves—covering maximum, minimum and average conditions for both sandstones and limestones—a fairly good coverage of the range of the most common types of producing formations was obtained.

Next in importance are the types of reservoir fluids within the rock. By means of the correlations established by Beal[16] and by Standing[18] the range of possible combinations was covered by choosing three different crude oil gravities, 15, 30 and 50° API, and solution gas-oil ratios ranging up to 2,000 cu ft/bbl. Selection of the crude oil gravity and the amount of gas in solution defines the viscosity and shrinkage relationships as well as the pressure and the temperature of the reservoir system.

To confine the computations to these main variables, the following simplifications were introduced:

1. The crude oil in the reservoir is at the bubble point.
2. There is no free gas cap.
3. There is no water influx.
4. There is no gravity drainage effect.
5. There is no injection of either gas or water.
6. Connate water is assumed to be 25 per cent in the sands and sandstones and 15 per cent in the limestones and dolomites.
7. The relative permeability ratio ($k_g/k_o$) is independent of the presence of an immobile connate water phase within the range of connate water values normally encountered[9].
8. There is no vaporization hysteresis.
9. The dissolved gas is assumed to follow an empirical relationship between gravity and saturation pressure, which ranges from 1.5 at lower pressures to .75 at higher pressures.
10. The producing reservoir is a porous medium uniform horizontally and vertically and containing oil, gas, and water in continuous equilibrium.
11. The abandonment pressure is 10 per cent of the initial pressure.
12. The effect of production rate, selective production, and well spacing is disregarded.
13. The computed pressure-saturation relationship at the reservoir boundary is representative of the average pressure-saturation relationship of the entire drainage area[3].

## DERIVATION AND SOLUTION OF THE DEPLETION EQUATION

The Equation of Continuity for Oil is obtained by setting the derivative with respect to time of the amount of oil present in a unit volume of reservoir rock equal to the difference between inflow and outflow. In a like manner the Equation of Continuity for Gas is derived. To simplify the solution of these two differential equations, only the reservoir boundary conditions are considered where the pressure gradient is zero. It is also assumed that the porosity and connate water saturation are constant and that the gas-oil ratio function $\frac{\mu_o}{\mu_g} \cdot \frac{k_g}{k_o}$ may be considered as essentially constant for small changes in oil saturation and pressure. After this simplification, the Equation for Gas is divided by the Equation for Oil, resulting in the following Depletion Equation:

$$\frac{\Delta S_o}{\Delta p} = \frac{S_o \left\{ \frac{1}{B_g} \left( \frac{s}{B_o} - \frac{\Delta B_g}{\Delta p} \right) + \frac{b}{B_o} \cdot \frac{\mu_o}{\mu_g} \cdot \frac{k_g}{k_o} \right\} + \left( \frac{1 - S_w}{B_g} \right) \frac{\Delta B_g}{\Delta p}}{1 + \frac{\mu_o}{\mu_g} \cdot \frac{k_g}{k_o}} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (13)$$

In this equation all symbols correspond to the nomenclature list at the end of this paper and are in accordance with the list of letter symbols for reservoir engineering approved by the Petroleum Branch Executive Committee of the AIME and published in the Jan. 1955, issue of the JOURNAL OF PETROLEUM TECHNOLOGY, except that $s$ replaces the derivative of solubility, $\frac{\Delta R_s}{\Delta p}$, which is assumed to be constant, and that $b$ replaces the derivative of the oil formation volume factor, $\frac{\Delta B_o}{\Delta p}$, which is also assumed to be constant. Both the solubility and oil formation volume factor curves appear to be essentially straight lines over the pressure interval between the assumed economic limit pressure and the bubble point pressure.

In solving the depletion equation numerically, the following factors — which are functions of pressure only — were first calculated at various intervals from the bubble point to the economic limit pressure:

$\frac{1}{B_g} \left( \frac{s}{B_o} - \frac{\Delta B_g}{\Delta p} \right)$, $\frac{b}{B_o} \cdot \frac{\mu_o}{\mu_g}$, and $\left( \frac{1-S_w}{B_g} \right) \frac{\Delta B_g}{\Delta p}$.

This total pressure range was then divided into 10 lb increments of $\Delta p$ and the above functions were obtained by interpolation.

In each individual computation the value of $S_o$ previously calculated was kept constant, which fixed the

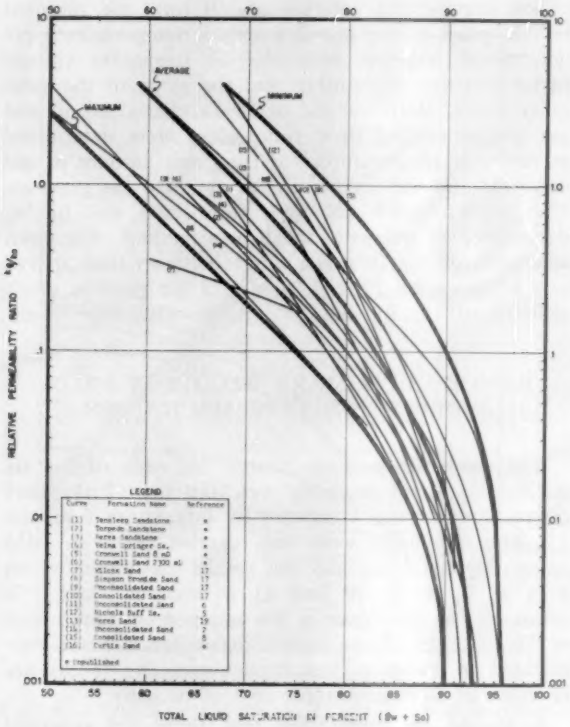


FIG. 1 — RELATIVE PERMEABILITY RATIO FOR SANDS AND SANDSTONES VS TOTAL LIQUID SATURATION.

$k_g/k_o$ value and determined for that step the values of $\frac{b}{B_o} \cdot \frac{\mu_o}{\mu_g} \cdot \frac{k_g}{k_o}$ and $1 + \frac{\mu_o}{\mu_g} \frac{k_g}{k_o}$.

By dropping the pressure over the small increment $\Delta p$ the corresponding drop in oil saturation $\Delta S_o$ was computed from the $\frac{\Delta S_o}{\Delta p}$ value given, which in turn led to the new $S_o$ value.

The process was then repeated until the abandonment pressure was reached.

From the initial oil saturation $S_o$ and the initial oil formation volume factor $B_o$ together with the oil saturation $S_o'$ and oil formation volume factor $B_o'$ at the economic limit, the recovery factor is then computed by means of:

$$\text{Recovery factor} = 77.58 \left( \frac{S_o}{B_o} - \frac{S_o'}{B_o'} \right) \text{ STB/acre-ft/per cent porosity.}$$

## THE RANGE OF RELATIVE PERMEABILITY-SATURATION RELATIONSHIPS

A search of recent literature on the subject showed a substantial number of relative permeability data for many different types of rock. This data together with some unpublished curves is reproduced on Fig. 1 for sands and sandstones and on Fig. 2 for limestone, dolomite, and chert formations. It may be noted that the range in the data on Fig. 1 is not as wide as it is on Fig. 2.

For the sand and sandstone computations three cases were selected, which are indicated on Fig. 1 with heavy lines and which are deemed to represent fairly well the entire possible range by providing a maximum, a minimum, and an average $k_g/k_o$ relationship. The maximum curve seems to be typical of unconsolidated sands, while the minimum curve appears to be more representative of highly cemented sandstones. The average curve can be considered typical of the average consolidated sand or sandstone.

For the limestone, dolomite and chert formations on Fig. 2 the spread in the $k_g/k_o$ curves is considerably wider. Fractured chert seems to be the steepest and most unfavorable. At the other end of the range no well defined maximum case is apparent, although the curve numbered 23, adopted from Bulnes and Fitting[13], representative of 26 samples from West Texas Permian dolomite, seems to be the best choice. The presence of intergranular or pinpoint-type porosity in limestones seems to point to a more favorable $k_g/k_o$ curve, although it is not readily understood why this curve should even be better than the one for unconsolidated sand. This also applies to the indicated critical gas saturation which is very high. The curve selected as more or less average on Fig. 2 appears to be typical of the vugular types of limestone.

## CHARACTERISTICS OF RESERVOIR OIL AND GAS

Correlations of the physical characteristics of oil and gas with the API gravity of the oil, specific gravity of the gas, bottom hole pressure, and bottom

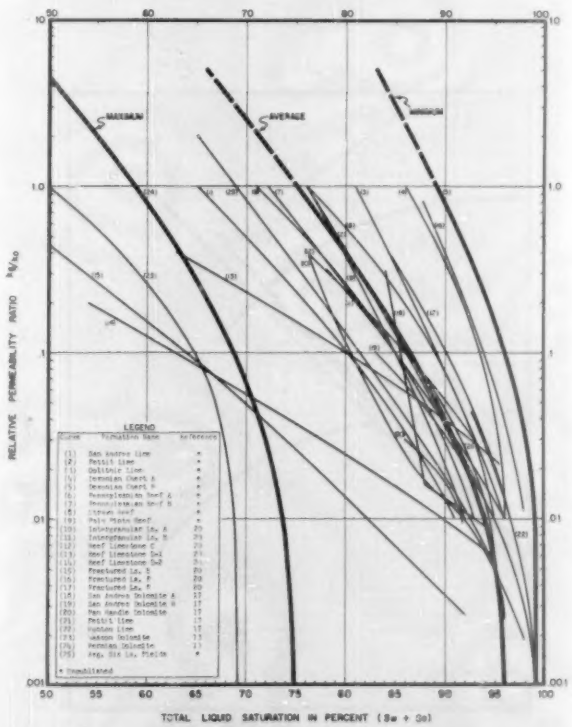


FIG. 2 — RELATIVE PERMEABILITY RATIO FOR LIMESTONE, DOLOMITE, AND CHERT FORMATIONS VS TOTAL LIQUID SATURATION.

hole temperature have been published by various investigators[4,7,9,16,18].

The significant characteristics of a saturated reservoir oil for the purpose of the depletion calculations are the viscosity ratio of oil to gas $\mu_o/\mu_g$, the formation volume factor for the oil $B_o$, the slope of the oil formation volume factor curve $b$, the slope of the gas solubility curve $s$, and the gas formation volume factor $B_g$.

The correlations established by Bicher and Katz[7], and by Beal[16] show the gas viscosity $\mu_g$ as a function of gas gravity, pressure, and temperature, and the oil viscosity $\mu_o$ as a function of gas-free crude oil gravity, temperature, and amount of gas in solution.

The correlations established by Standing[18] show the gas solubility and the oil formation volume factor $B_o$ for a given pressure, temperature, oil gravity, and gas gravity.

The combination of these correlations therefore made it possible to determine all the significant characteristics of a "synthetic" saturated reservoir oil when the oil gravity and the total amount of gas in solution were given. In order to make this determination, a solution gas gravity was needed and an empirical relationship between the gravity of gas in solution and the bubble point pressure was assumed.

To cover the possible range of oil gravities with a low, high, and intermediate value for interpolation purposes, the characteristics of synthetic saturated oils were computed for gas-free crude oil gravities of 15°, 30° and 50° API. A range of solution gas-oil ratios of 60, 200, 600, 1,000 and 2,000 cu ft/bbl was then combined with the three chosen oil gravities to yield the necessary saturated crude oil systems.

By means of Standing's charts for each combination of oil gravity and solution gas-oil ratio the required bubble point pressure and reservoir temperature were determined, together with the oil formation volume factor-pressure relationship and the slope of the solubility curve. With the aid of Beal's charts the oil and gas viscosities and their ratio $\mu_o/\mu_g$ were determined at reservoir temperatures for the given amount of gas dissolved and the forementioned assumed gas gravities. The gas formation volume factor curve was further determined by means of the Brown method[4]. The characteristics of the synthetic oil-gas systems thus arrived at are shown on Figs. 3, 4, and 5 for gas-free crude gravities of 15, 30, and 50° gravity API, respectively.

## RANGE OF PRIMARY RECOVERY FROM A DEPLETION TYPE MECHANISM

The saturation-pressure history for each of the six different types of reservoir rock and the 12 synthetic oil-gas systems was computed by integrating Equation 13. The numerical work was carried out with IBM computing machines and the results are presented on Figs. 6, 7, 8, 9, 10 and 11 as recovery factor vs pressure. The recoveries at the assumed economic limit of 10 per cent of the bubble point pressure are enumerated in Table 1. For convenience the results are in terms of STB/acre-ft/per cent of porosity.

It should be emphasized that there are potential hazards in using generalized recovery data of this type. It is always preferable to use the actual physical data on reservoir rock and its contents, when such data is available. This is oftentimes not the case, however, certainly not during the initial stages of the development of an oil field, when information on potential recoveries is most needed. The data presented in Table 1 may then

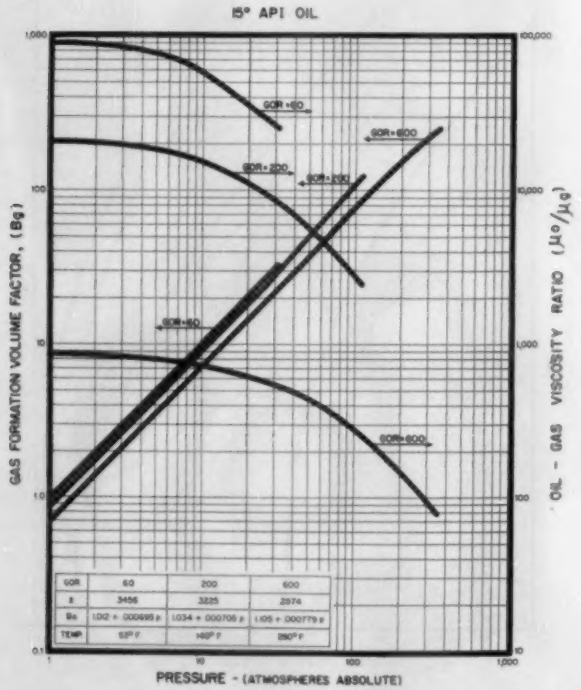
15° API OIL
GOR=60
GOR=600
GOR=200
GOR=2K
GOR=60
GOR=600
GAS FORMATION VOLUME FACTOR, (Bg)
OIL - GAS VISCOSITY RATIO (μo/μg)
PRESSURE - (ATMOSPHERES ABSOLUTE)
GOR | 60 | 200 | 600
P | 3456 | 3325 | 2974
Bo | 1.012 + .000695 p | 1.034 + .000706 p | 1.05 + .000779 p
TEMP | 93° F | 140° F | 250° F

FIG. 3 — GAS FORMATION VOLUME FACTOR AND OIL-GAS VISCOSITY RATIO VS PRESSURE FOR 15° API OIL.

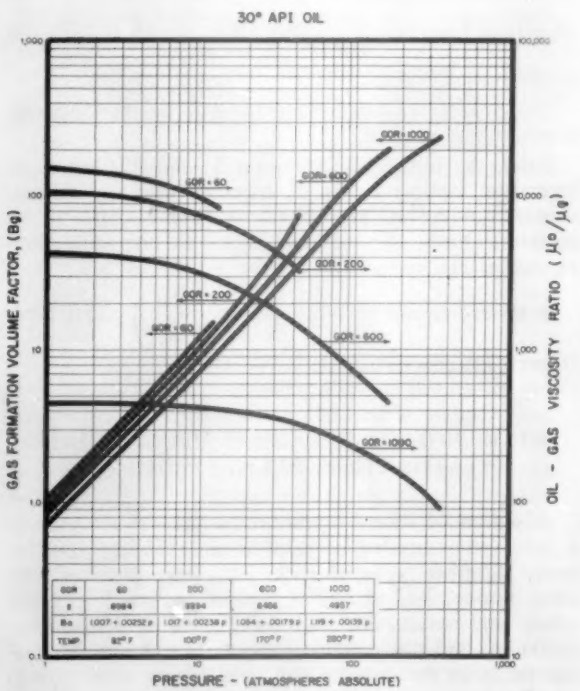
30° API OIL
GOR=1000
GOR=60
GOR=800
GOR=200
GOR=200
GOR=60
GOR=600
GOR=1000
GAS FORMATION VOLUME FACTOR, (Bg)
OIL - GAS VISCOSITY RATIO (μo/μg)
PRESSURE - (ATMOSPHERES ABSOLUTE)
GOR | 60 | 200 | 600 | 1000
P | 6084 | 5334 | 6456 | 4957
Bo | 1.007 + .0025 p | 1.017 + .00238 p | 1.084 + .00179 p | 1.19 + .00139 p
TEMP | 82° F | 100° F | 170° F | 220° F

FIG. 4 — GAS FORMATION VOLUME FACTOR AND OIL-GAS VISCOSITY RATIO VS PRESSURE FOR 30° API OIL.

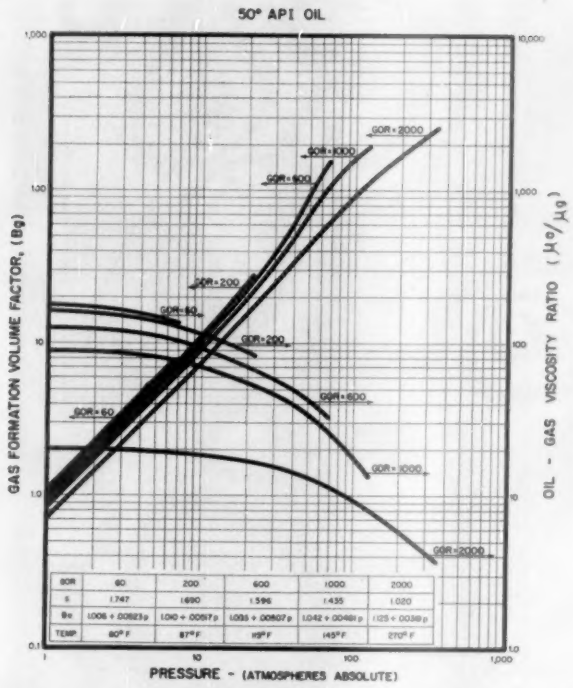
50° API OIL
GAS FORMATION VOLUME FACTOR, (Bg)
OIL - GAS VISCOSITY RATIO ( μo/μg )
PRESSURE - (ATMOSPHERES ABSOLUTE)
GOR=2000
GOR=1000
GOR=600
GOR=200
GOR=60
GOR=200
GOR=600
GOR=1000
GOR=2000
GOR | 60 | 200 | 600 | 1000 | 2000
B | 1.747 | 1.690 | 1.596 | 1.435 | 1.020
Bo | 1.006 + .00823 p | 1.010 + .00517 p | 1.035 + .00807 p | 1.042 + .00481 p | 1.025 + .00389 p
TEMP | 80° F | 87° F | 119° F | 145° F | 270° F

FIG. 5 — GAS FORMATION VOLUME FACTOR AND OIL-GAS VISCOSITY RATIO VS PRESSURE FOR 50° API OIL.

be helpful in establishing the possible range of such recoveries.

## COMPARISON WITH ACTUAL RECOVERIES

In a study made by the well spacing committee of the API[12] the indicated recoveries of a number of actual reservoirs are listed, together with the data on porosity, gas in solution, shrinkage, etc. On the chart of Fig. 12 the recoveries of these reservoirs designated as being of the depletion or solution gas drive type are plotted against the reported crude oil gravity. This data is supplemented by other recoveries taken from the literature. When known, gas-oil ratios are shown near the individual points. On this same chart are also shown the calculated recovery curves for the three types of sandstones and three types of limestones for a gas-oil ratio of 400 cu ft/bbl.

TABLE 1 — PRIMARY RECOVERY IN STOCK TANK BARRELS PER ACRE-FOOT PER PER CENT POROSITY FOR DEPLETION TYPE RESERVOIRS

| Oil Solution GOR Cu Ft/Bbl | Oil Gravity ° API | Sand or Sandstone | | | Limestone, Dolomite or Chert | | |
|---|---|---|---|---|---|---|---|
| | | Maximum | Average | Minimum | Maximum | Average | Minimum |
| 60 | 15 | 7.22 | 4.87 | 1.44 | 17.87 | 2.56 | .36 |
| | 30 | 11.95 | 8.52 | 4.88 | 20.87 | 6.29 | 1.85 |
| | 50 | 19.20 | 13.89 | 9.46 | 24.78 | 11.84 | 5.07 |
| 200 | 15 | 6.97 | 4.62 | 1.75 | 16.33 | 2.65 | .51 |
| | 30 | 11.57 | 7.90 | 4.38 | 19.05 | 5.75 | 1.52 |
| | 50 | 19.42 | 13.73 | 9.15 | 23.44 | 11.40 | 4.36 |
| 600 | 15 | 7.56 | 4.76 | 2.50 | 12.69 | 3.29 | .90 |
| | 30 | 10.48 | 6.52 | 3.61 | 14.64 | 4.70 | (1.24) |
| | 50 | 15.05 | 9.74 | 5.85 | 17.30 | 7.25 | (2.06) |
| 1,000 | 15 | — | — | — | — | — | — |
| | 30 | 12.34 | 7.61 | 4.52 | 13.26 | 5.38 | (1.63) |
| | 50 | 11.96 | 7.15 | 4.10 | 12.79 | 4.83 | (1.24) |
| 2,000 | 15 | — | — | — | — | — | — |
| | 30 | — | — | — | — | — | — |
| | 50 | 10.58 | 6.45 | 4.04 | 9.64 | (4.26) | (1.47) |

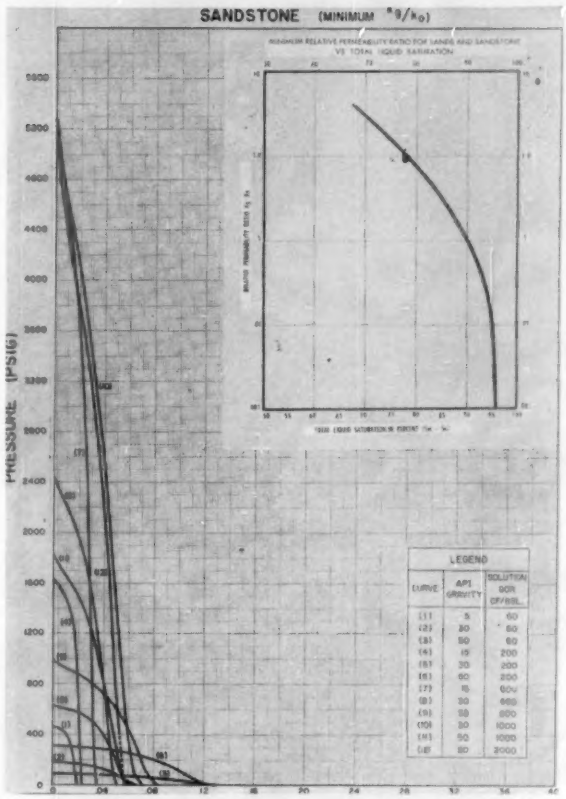


FIG. 6 — SATURATION-PRESSURE HISTORY OF SANDSTONE WITH MINIMUM $k_g/k_o$.

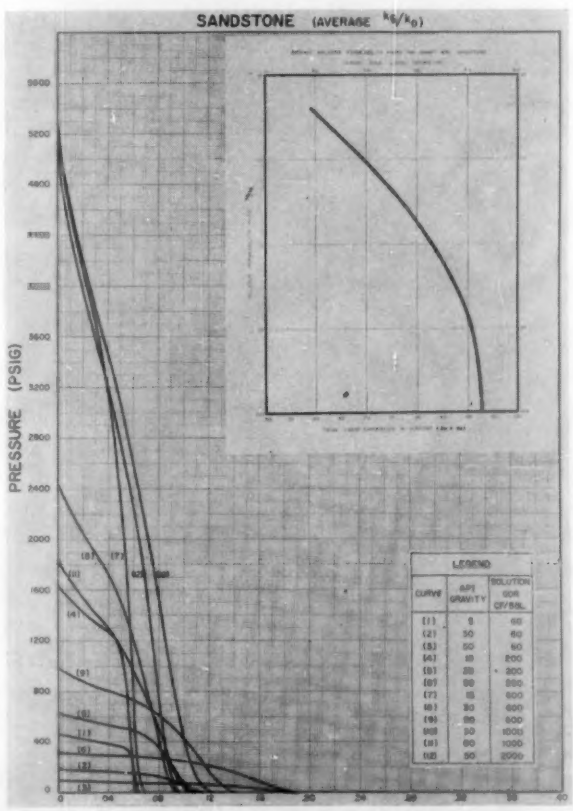


FIG. 7 — SATURATION-PRESSURE HISTORY OF SANDSTONE WITH AVERAGE $k_g/k_o$.

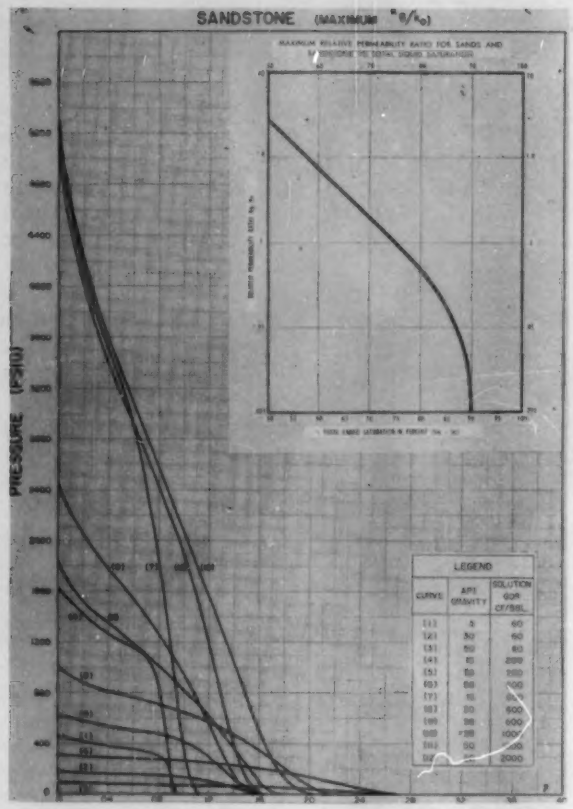


FIG. 8 — SATURATION-PRESSURE HISTORY OF SANDSTONE WITH MAXIMUM $k_g/k_o$.

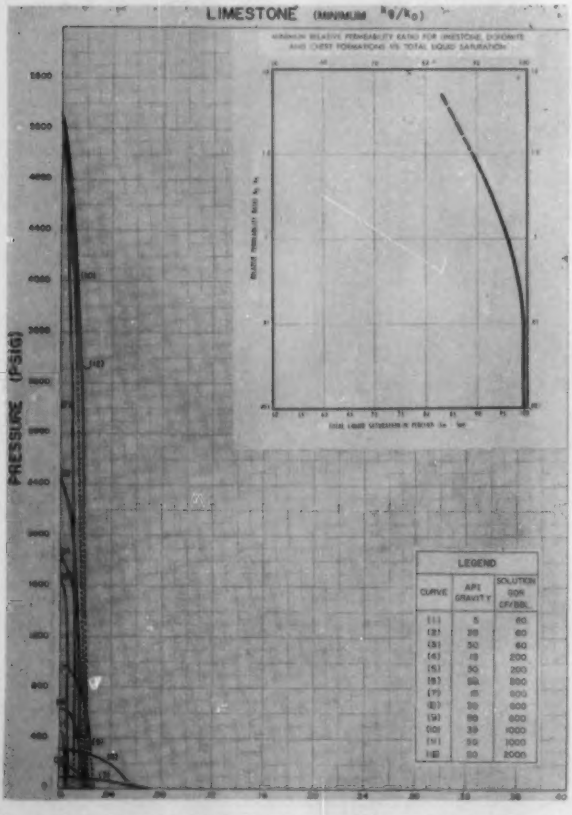


FIG. 9 — SATURATION-PRESSURE HISTORY OF LIMESTONE WITH MINIMUM $k_g/k_o$.

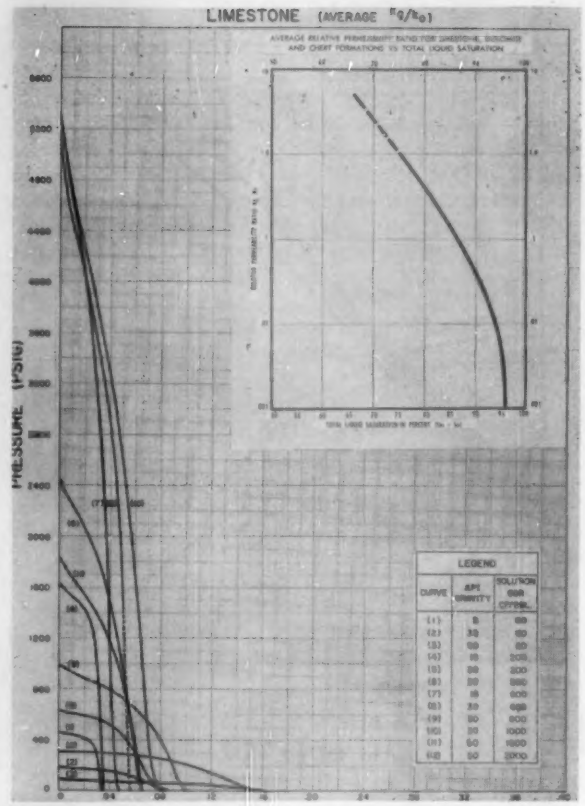


FIG. 10 — SATURATION-PRESSURE HISTORY OF LIMESTONE WITH AVERAGE $k_g/k_o$.

As can be seen from Fig. 12, most of the points fall well within the range indicated by the different curves, which in turn supports the validity of the methods used. It is believed that the few fields which show recoveries higher than indicated by the maximum curves are probably aided by either a partial water drive or gravity drainage effects.

## CONCLUSIONS

1. Recovery factors in line with those indicated by actual depletion type reservoirs can be obtained from the depletion equation using published correlations of physical characteristics of oil, gas, and reservoir rock.
2. The recovery of oil from a depletion type reservoir can be correlated with the solution gas-oil ratio, the API gravity, and the type of reservoir rock.

## NOMENCLATURE

| *Symbol* | *Definition* | *Units* |
|---|---|---|
| $\mu_o$ | Reservoir oil viscosity. | centipoises |
| $\mu_g$ | Reservoir gas viscosity. | centipoises |
| $k_o$ | Effective permeability to oil. | Darcies |
| $k_g$ | Effective permeability to gas. | Darcies |
| $S_o$ | Oil saturation as fraction of total pore space. | fraction |
| $S_w$ | Water saturation as fraction of total pore space. | fraction |
| $\Delta$ | Difference symbol. | |

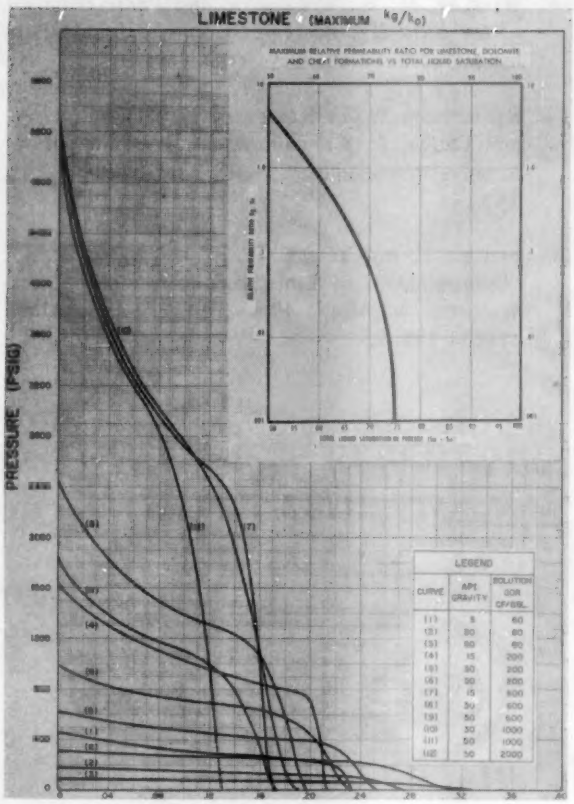


FIG. 11 — SATURATION-PRESSURE HISTORY OF LIMESTONE WITH MAXIMUM $k_g/k_o$.

| | | |
|---|---|---|
| $B_o$ | Oil formation volume factor expressed as the ratio of the reservoir oil volume to the stock tank oil volume. | ratio |
| $B_g$ | Gas formation volume factor expressed as the ratio of the volume of gas under standard conditions to the volume of gas under reservoir conditions. | ratio |
| $p$ | Reservoir pressure. | atmospheres absolute |
| $R_s$ | Solution gas-oil ratio expressed as volume of gas under standard conditions to volume of stock tank oil. | ratio |
| $s$ | Derivative of solubility-pressure function $\frac{\triangle R_s}{\triangle p}$. | ratio (constant) |
| $b$ | Derivative of oil formation volume factor-pressure function $\frac{\triangle B_o}{\triangle p}$. | ratio (constant) |

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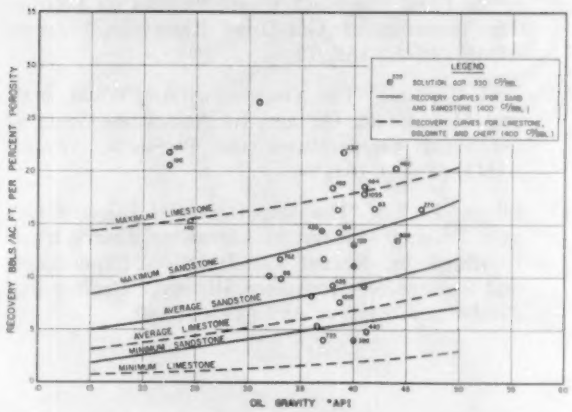


FIG. 12 — RECOVERY IN BARRELS PER ACRE-FOOT/PER CENT POROSITY VS OIL GRAVITY ° API.


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# ANALYSIS of RESERVOIR PERFORMANCE $k_g/k_o$ CURVES and a LABORATORY $k_g/k_o$ CURVE MEASURED on a CORE SAMPLE

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## ABSTRACT

*Two methods are used to obtain the relationship between ratio of gas to oil permeability and gas saturation. One method is to calculate a curve from field measurements of reservoir behavior: the other is to measure the relationship on a core sample in the laboratory. The curves resulting from these two methods are often compared and seldom found to agree. The most important reason for the nonagreement is often overlooked. This reason is that the performance $k_g/k_o$ curve is calculated with the assumption of uniform pressure and saturation throughout the reservoir.*

*To show the difference between performance type $k_g/k_o$ curves and laboratory type $k_g/k_o$ curves, two performance type $k_g/k_o$ curves for two different production rates were calculated from the production performance of a hypothetical reservoir for which a laboratory type curve was assumed. Production performance of the hypothetical reservoir was calculated by use of International Business Machine's 701 Computer. The performance type $k_g/k_o$ curves differed from the laboratory curve for the hypothetical reservoir. The performance type curve for the lowest production rate most nearly coincided with the laboratory curve.*

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## INTRODUCTION

Predictions of oil reservoir performance are often made with the aid of complex numerical calculations. An important quantity required in these calculations is the ratio of gas permeability to oil permeability ($k_g/k_o$) at a particular gas saturation. Two methods are used to obtain a relationship between this ratio and gas saturation. The curves resulting from these two methods are called performance $k_g/k_o$ curves and laboratory $k_g/k_o$ curves.

The performance curve is obtained from field measurements of reservoir behavior. Particular $k_g/k_o$ values are calculated from the producing gas-oil ratio, the cumulative reservoir withdrawals, the original oil in place, the average reservoir pressure, and the PVT properties of the reservoir fluids. The particular $k_g/k_o$ values are then plotted against the average reservoir gas saturations for the entire history period. In order to use this derived $k_g/k_o$ relationship for performance predictions, a curve through these points is extrapolated to higher gas saturations.

The laboratory $k_g/k_o$ curve is obtained from measurements made on core samples. Saturation is maintained uniform throughout the core during these measurements.

The $k_g/k_o$ curves obtained with these two independent methods are often compared and seldom are found to be the same. Various reasons have been offered for the lack of correlation. One is that insufficient cores were obtained to derive a curve representative of the reservoir rock. Another is that laboratory methods have failed to reproduce reservoir conditions. The most important reason for the noncorrelation has been often overlooked because of the difficulty in evaluating its effect. This reason is that the performance or field $k_g/k_o$ curve is calculated with the assumption of uniform pressure and saturation throughout the reservoir. In any

reservoir producing fluids there must be a pressure and saturation gradient, even though those gradients be small. Therefore, the assumption of uniformity never is fulfilled in practice.

Results presented in this paper snow that the performance $k_g/k_o$ curve should never correspond to the laboratory derived curve. The method used to demonstrate the difference in the two curves was to calculate the performance of an example reservoir. This reservoir was a radial system 800 ft in diameter producing into a 9⅝ in diameter well. Porosity and specific permeability were assumed to be uniform throughout the reservoir. The relative oil and gas permeabilities were assumed to be only a function of saturation. The fluid viscosity and phase properties were assumed to be only a function of pressure. Two production schedules were used for the reservoir. The saturation and pressure gradients at specific times for each schedule were calculated by IBM's 701 Computer. Calculation of the performance $k_g/k_o$ curve for this reservoir showed that each performance curve differed markedly from the laboratory curve.

The need for this analysis arose while studying specific oil reservoirs. In those studies, the performance and laboratory $k_g/k_o$ curves for a particular reservoir differed by a larger amount than could be attributed to errors in field or laboratory measurements.

## METHODS OF OBTAINING $k_g/k_o$ CURVES

### Laboratory $k_g/k_o$ Curve

Laboratory measurements of oil and gas permeabilities usually are performed on 1-in core plugs. Equipment used in these measurements has been designed to maintain a constant saturation throughout the core during a particular measurement. Recent experiments in the laboratory have been made on cores 12 in long and 2½ in. in diameter. In these tests, even though a measureable saturation gradient existed along the core length, measurements were made with respect to a small length wherein the saturation was essentially constant. The result of these experiments is that laboratory $k_g/k_o$ values refer to a specific saturation at a particular point in a porous medium.

Many laboratory measurements have been made by California Research Corp.[1] and other research laboratories.[2] All results of these measurements gave the same general shape of relative permeability curves. The curves of oil and gas permeabilities presented in Fig. 1 are typical of these results. They do not refer to any particular sandstone, but were selected as being representative of an average consolidated reservoir sand.

One important feature of all laboratory relative permeability curves is the existence of a critical gas saturation. In this paper critical gas saturation is defined as the largest gas saturation that can exist in a porous medium subjected to a pressure gradient without movement of free gas. The critical gas saturation shown on Fig. 1 is 10 per cent. The previously mentioned references have found critical gas saturations in the range between 5 and 20 per cent.

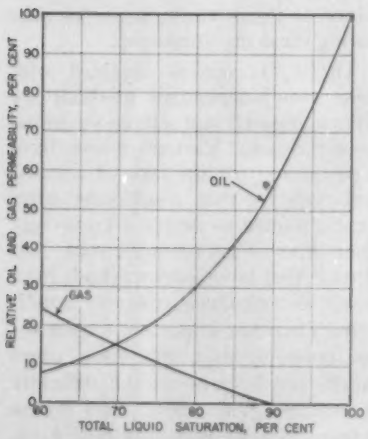


FIG. 1 — LABORATORY RELATIVE GAS AND OIL PERMEABILITY VS TOTAL LIQUID SATURATION.

### Reservoir Performance $k_g/k_o$ Curve

In order to obtain a reservoir performance $k_g/k_o$ curve, the performance of a particular reservoir must be known. In this particular study, the reservoir performance was calculated for a hypothetical reservoir. The first step in calculating the performance of the example reservoir was to select specific values of rock and fluid properties that were representative of typical oil reservoirs. The relative gas and oil permeability saturation relationships used for the example reservoir performance calculation were the laboratory curves given in Fig. 1. The basic fluid properties are given in Figs. 2 and 3. They were obtained from general correlations[3, 4] for a hydrocarbon system composed of a 40° API oil and 0.7 gravity gas. The bubble point pressure of the system is assumed to be 5,000 psia. The reservoir temperature is assumed constant at 180° F. Initial pressure of the reservoir is assumed to be at the bubble point.

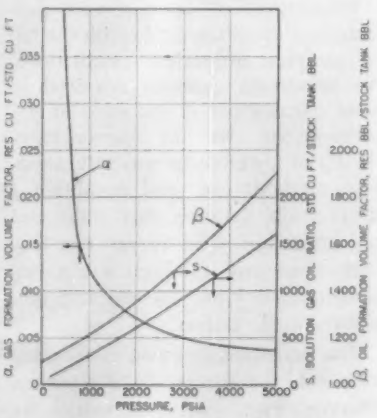


FIG. 2 — OIL AND GAS PHASE RELATIONSHIPS VS PRESSURE.

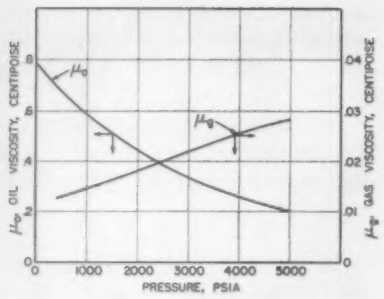


FIG. 3 — OIL AND GAS VISCOSITY VS PRESSURE.

The example reservoir is a radial system with outer boundary radius of 400 ft, a wellbore diameter of 9⅝ in and a thickness of 100 ft. Reservoir behavior was calculated for two production schedules. In each schedule the reservoir was produced at a constant rate until the flowing bottom hole pressure was reduced to 500 psia. At that point the flowing pressure was held constant and the production rate dictated by the reservoir characteristics. The two initial oil rates were 1,000 and 100 B/D.

These calculations were performed by IBM's 701 Computer. Satisfactory numerical methods[5] have been recently obtained for solving the equations of unsteady-state two-phase flow in oil reservoirs. The pressure and saturation distributions for the 1,000 B/D initial rate at five different times are plotted on Figs. 4 and 5. The pressure and saturation distributions for the 100 B/D initial rate are plotted on Figs. 6 and 7.

Fluid flow at every point in the example reservoir was governed by

[1]References given at end of paper.

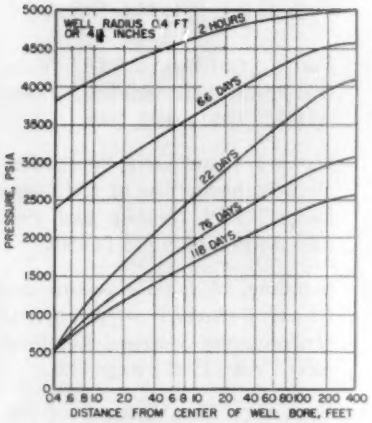


FIG. 4 — PRESSURE VS DISTANCE FROM CENTER OF WELLBORE, 1,000 B/D INITIAL RATE.

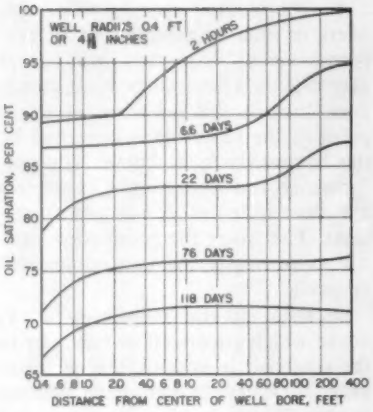


FIG. 5 — OIL SATURATION VS DISTANCE FROM CENTER OF WELLBORE, 1,000 B/D INITIAL RATE.

the specific fluid and rock relationships given in Figs. 1, 2, and 3. The equation relating the flowing gas-oil ratio to these variables for a specific pressure and saturation is as follows:

$$R = S + 5.615\left(\frac{k_g}{k_o}\right)\left(\frac{\mu_o}{\mu_g}\right)\left(\frac{\beta}{\alpha}\right) \quad \ldots\ldots\ldots (1)$$

where

$R$ = flowing GOR, std cu ft/STB
$S$ = solution GOR, std cu ft/STB
$\frac{k_g}{k_o}$ = ratio of gas permeability to oil permeability
$\frac{\mu_o}{\mu_g}$ = ratio of oil viscosity to gas viscosity
$\beta$ = oil formation volume factor, reservoir bbl/STB
$\alpha$ = gas formation volume factor, reservoir cu ft/std cu ft

Equation 1 is used by field engineers to calculate reservoir performance $k_g/k_o$ curves. The quantities used by field engineers to evaluate Equation 1 are as follows: (1) the average static reservoir pressure; (2) the average reservoir gas saturation; and (3) the producing gas-oil ratio.

Specifically in Equation 1, the producing gas-oil ratio is entered as $R$; the solution gas-oil ratio, viscosities, and formation volume factors are selected at the average reservoir pressure and entered as $S$, $\mu_o$, $\mu_g$, $\beta$, and $\alpha$; and Equation 1 is solved for $k_g/k_o$. The resultant $k_g/k_o$ is then plotted against the corresponding average reservoir gas saturation. Use of Equation 1 in this manner presupposes that no pressure or saturation gradients exist in the reservoir. In practice this assumption is never true because the producing gas-oil ratio is measured at the wellbore face which under producing conditions has a lower pressure than the field average. Therefore, an equation that refers to a particular point is used with quantities that pertain to different points in the reservoir.

## RESULTS

After the IBM 701 Computer calculated the saturation and pressure distributions existing in the example reservoir at different times, results were available that permitted calculation of a field performance $k_g/k_o$ curve for the example reservoir in the same manner that is used by field engineers. Two performance $k_g/k_o$ curves are given in Fig. 8 that correspond to the two production schedules. Also, the laboratory $k_g/k_o$ curve is given in Fig. 8 for comparison. Although the performance $k_g/k_o$ curves are restricted to the example reservoir produced with the chosen programs, the general position of the performance curves with respect to the laboratory curve should be characteristic of all performance $k_g/k_o$ curves.

One striking feature of the performance $k_g/k_o$ curve is that the critical gas saturation has shifted to a lower value than that of the laboratory curve. The reason for this is evident when one considers that free gas may be flowing from a small volume at the lower pressure in the neighborhood of the borehole with no free gas flowing from the remaining large volume of the reservoir at the higher pressure. Thus, $k_g/k_o$ can be greater than zero for average reservoir gas saturations that are much less than the critical gas saturation of the laboratory measurement.

Another feature of the performance curve, particularly that one associated with the 1,000 B/D initial oil rate, is the several pronounced humps. The laboratory curve in comparison is monotonic. The changes in curve shape were associated with pressure and saturation transients and the change in production program when the flowing bottom hole pressure fell to the minimum value.

All differences between the two type curves given in Fig. 8 are caused by calculating gross reservoir behavior with an equation that refers to a particular point in the reservoir.

## CONCLUSIONS

If the relative permeability curves used in this study describe simultaneous flow of gas and oil in a solution gas drive reservoir, then the following conclusions can be made:

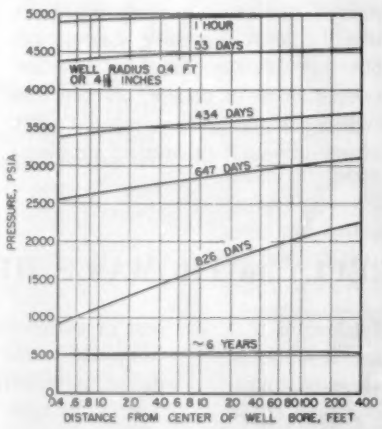


FIG. 6 — PRESSURE VS DISTANCE FROM CENTER OF WELLBORE, 100 B/D INITIAL RATE.

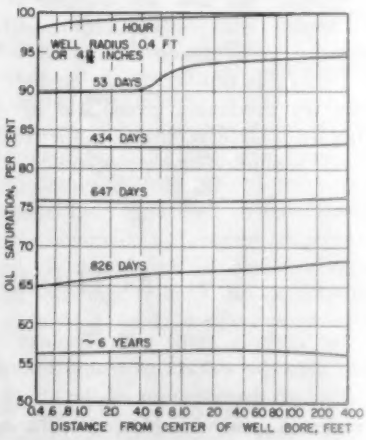


FIG. 7 — OIL SATURATION VS DISTANCE FROM CENTER OF WELLBORE, 100 B/D INITIAL RATE.

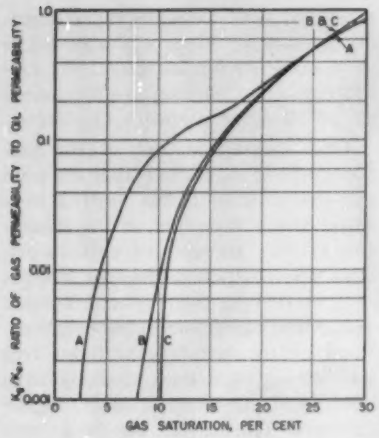


FIG. 8 — RATIO OF GAS PERMEABILITY TO OIL PERMEABILITY VS GAS SATURATION.

Curves A and B are calculated from the production performance of the hypothetical reservoir; for Curve A initial production rate was 1,000 B/D, and for Curve B initial production rate was 100 B/D. Curve C was measured in laboratory on a core sample and was part of basic data used in calculations to obtain production performance of hypothetical reservoir.

1. The method used by field engineers in making calculations of performance $k_g/k_o$ curves will never give exactly a laboratory $k_g/k_o$ curve, even though the behavior of every point in the reservoir is governed by the laboratory $k_g/k_o$ curve. The performance and laboratory $k_g/k_o$ curves are most different at low gas saturations. The lower the production rate, the more nearly the two curves will coincide.

2. Even if the laboratory $k_g/k_o$ curve which governs flow behavior in the reservoir is smooth, the performance $k_g/k_o$ curve can have distinct humps. These humps are associated with transient behavior of the reservoir and changes in production program. Therefore, the extrapolation of the performance type curve for prediction purposes should be done with caution.

3. The best use of laboratory $k_g/k_o$ curves could be achieved by calculating reservoir behavior on a high speed digital computer such as an IBM 701.

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# DISCUSSION


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This paper demonstrates a major cause for the difference between laboratory and field performance $k_g/k_o$ data. However, since laboratory measurements of fluid and rock properties do not exactly represent the reservoir, there is some question as to whether the time and expense of the accurate numerical procedure and machine computation advocated in this paper is justified at the present time for predicting gross field performance. Until variations in the reservoir geometry and properties can be sufficiently defined, we might ask if the errors in the results obtained when assuming idealized geometry and uniform permeability and porosity are much less than the errors obtained with the additional assumption of uniform saturation. The answer may well be yes and that the improved accuracy justifies the more lengthy and expensive calculation, but this question has not been answered. It is, of course, obvious that such a calculation is warranted when examining such theoretical problems as the effect of rate on recovery, but the question we ask concerns the prediction of reservoir performance for engineering purposes.

In their Conclusion 2, the authors caution the reader against extrapolating performance $k_g/k_o$ data for prediction purposes. With laboratory data and the standard calculating procedures, no extrapolation should be necessary. The field data and the authors' explanation for the difference between laboratory and field data should then serve as a check on the reasonableness of the results.

# AUTHORS' REPLY to THOMAS S. HUTCHINSON

The authors agree with Thomas S. Hutchinson that field data are subject to many inaccuracies. It seems to us that an investigation of the affect of these inaccuracies could easily be done with the aid of a high speed computing machine. It is interesting to note that the cost of computing reservoir behavior with a high speed computer, once computer procedures have been completed, is relatively low. For example, a complete solution of the type given in the paper costs less than $100.

★★★

# A METHOD for NEUTRON DERIVED POROSITY DETERMINATION for THIN BEDS

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## ABSTRACT

*The application of the Scintillometer to radioactivity surveys in boreholes of oil wells has made it possible to determine bed thickness with a high degree of accuracy. This fact, combined with known relation of logging variables, makes thin bed porosity determination practical.*

*With the use of the Scintillometer a method has been derived whereby the apparent level of radiactivity, as recorded on radiation logs, may be converted to the true level. The true level of radioactivity is that level to which the recording pen would have traveled had the detector remained at a given depth for an infinitely long period of time. This factor is:*

$$R_t/R_a = \frac{L/D}{\text{Log}_e \dfrac{e^{L/D} \times e^{T/D}}{e^{L/D} + e^{T/D} - 1}}$$

where $R_t$ is the true radioactivity level, $R_a$ is the apparent radioactivity level, $T$ is the bed thickness, $D$ is drag, and $L$ is the length of the detecting system. This method depends entirely on accurate measurements of bed thickness and drag. A thorough discussion of the concept of time constant and logging speed as related to drag is undertaken.

## INTRODUCTION

Neutron curve interpretation has become one of the accepted methods for porosity determination in oil field practices. A great deal of literature has been published about neutron derived porosities, but this has been concerned with thick beds, or possibly even averaging of a series of thin beds as a single unit. There has been a lack of written information on methods whereby porosity can be evaluated for beds less than 10 ft in thickness.

In certain areas, production is derived from relatively thin formations. The importance of thin bed evaluation, the fact that the Scintillometer is an adequate tool for this application, and the general lack of published information concerning neutron porosity for thin beds are the fundamental reasons for presenting this method of porosity determination. This concept is not put forth with the idea of discounting existing methods, but is merely suggested as a modification of other accepted methods of porosity determination which makes no allowance for quantitative evaluation of thin beds. The effects on the neutron log of counting statistics, statistical variation in the porosity of earth materials, and hole size must be taken into account to obtain neutron derived porosities. Since these effects have been described in past literature, the authors have not made an attempt to go into the subject in detail. With the use of statistical and repeated sections on the log, it may be determined which responses on the log actually correspond with lithologic changes.

## EFFECT OF DRAG AND ITS RELATIONSHIP TO TIME CONSTANT AND LOGGING SPEED

Before entering into a discussion of porosity determination of thin beds, there should be a thorough

[1]References given at end of paper.

Paper presented at Pacific Petroleum Chapter Fall Meeting in Los Angeles Oct. 7-8, 1954, and at Petroleum Branch Fall Meeting in San Antonio Oct. 17-20, 1954. Original manuscript received in Petroleum Branch office on Aug. 2, 1954. Revised manuscript received May 11, 1955.

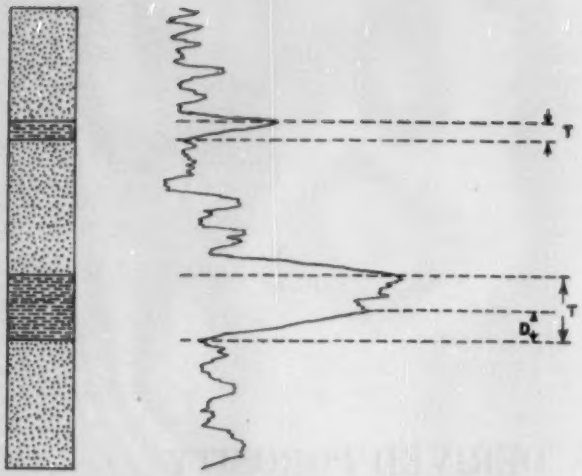


FIG. 1 — SHOWING THE EFFECT OF DRAG AND BED THICKNESS ON THE GAMMA RAY CURVE. THE UPPER SHALE REPRESENTS A TYPICAL THIN BED. $D$ = DRAG, T = BED THICKNESS.

understanding of the concept of drag, as related to time constant and logging speed.

1. *Drag* is the vertical distance travelled by the logging tool in the hole while the recording pen is responding to an abrupt change of radioactivity level at the boundary of adjacent beds (see Fig. 1). Because of the time constant of the recording and counting instruments, the recording pen will not respond instantly to an abrupt change in level of radioactivity to which the Scintillometer may be exposed. For thin beds maximum deflection may never be reached. For thicker beds, the pen will approach a maximum deflection which corresponds to the true radioactivity level of the formation. Drag is defined by the following equation:

$$\text{Drag (ft)} = \frac{\text{Line Speed (ft/min)} \times \text{Time Constant (sec)}}{60}$$

2. *Time constant* is the time required for the response of the recording device to drop 1/eth of its original value, or to reach about 2/3 of its final value, when the cause of the response is removed. The symbol "e" denotes the base of the naperian logarithm and is equal to 2.718.

Time constant is expressed in seconds and in common logging use may vary from 1 second to 30 seconds. It is normally set prior to recording the log and is therefore always known. Logging equipment should be equipped with surface control of time constant in order that it can be changed whenever necessary during a logging operation.

A series of typical logs run over the same interval with a constant logging speed, and with changes in time constant settings is shown in Fig. 2. Note that as time constant is increased, drag increases proportionately.

3. *Logging speed* is the rate at which the detecting instrument is traveling through the borehole. It is expressed in feet per minute. Fig. 3 shows the same logged interval with a fixed time constant setting but with varying logging speeds.

## THIN BED POROSITY DETERMINATION

It was noticed by the authors that in comparing

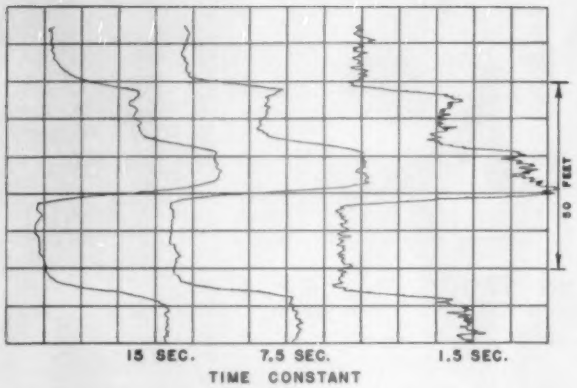


FIG. 2 — OUT HOLE NEUTRON LOG, SHOWING THE EFFECT OF CHANGING TIME CONSTANT WHILE MAINTAINING A CONSTANT LOGGING SPEED (15 FT/MIN).

neutron logs with core data, there was an excellent degree of correlation. By plotting porosity values on semi-logarithmic paper with porosity plotted logarithmically as the ordinate and with deflection from the zero line (the level of zero radioactivity) as the abscissa, porosity values fell along a straight line with a high degree on continuity.

It was also noted that porosity values for thin beds (beds less than 10 ft in thickness) fell either well above or well below the curve, not corresponding to the points as determined from neutron deflection in thicker beds. Consequently, a correction factor was calculated, which, when applied to the thin beds, placed the points either on or very near the curve (Fig. 4).

The correction factor is based upon the fact that in radioactivity logging the recording pen does not reach its maximum deflection in thin beds because of the influence of drag. This method calculates the point to which the pen would have traveled laterally disregarding the influence of drag, assuming an infinitely slow logging speed and an infinitely short time constant.

A formula has been derived whereby the relationship between true radioactivity and apparent radioactivity may be calculated. The formula depends upon the true thickness of the thin bed and the drag char-

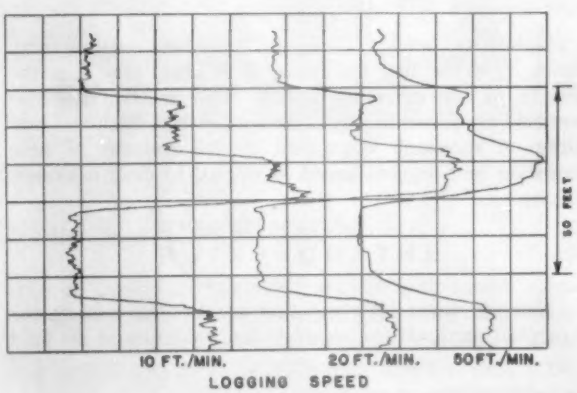


FIG. 3 — OUT HOLE NEUTRON LOG, SHOWING THE EFFECT OF CHANGING LOGGING SPEED WHILE MAINTAINING A CONSTANT TIME CONSTANT (4.5 SECONDS).

acteristics for the particular log. The formula may be stated as follows:

$$\frac{R_t}{R_a} = \frac{L/D}{\text{Log}_e \dfrac{e^{L/D} \times e^{T/D}}{e^{L/D} + e^{T/D} - 1}}$$

where $R_t$ = true radioactivity; $R_a$ = apparent radioactivity; $L$ = length of detecting system; $T$ = bed thickness; and $D$ = drag.

In reference to Fig. 5, $S_2$ is the deflection which the pen would have reached assuming an infinitely slow logging speed and an infinitely small time constant. $S_1$ is the deflection which the pen actually records on the neutron log. $S_2$ can be determined as the product of $S_1$ and the calculated value of $R_t/R_a$. The value of $S_2$ so determined is then used in conjunction with a calibration curve of the type shown in Fig. 4 to obtain the porosity of the thin bed in question.

By using the curve (Fig. 6) with $R_t/R_a$ plotted logarithmically as the ordinate and $T/D$ plotted as the linear abscissa, a great deal of the mathematics of the problem can be eliminated.

In the past it has been rather difficult to accurately determine the value of bed thickness, $T$, which is required in the above equation for $R_t/R_a$. This resulted from the fact that the length of instruments used for detection was so great that it was impossible to pinpoint formation breaks. With the advent of the Scintillometer into radiation logging, the problem has been simplified, since formation breaks may be determined to accuracies within a few inches. Since the instrument is only a few inches in length, it may be assumed that it is essentially a point-type indicator.

Because of the spacing factor between the neutron source and the neutron counter, formation breaks are not as accurately determined from the neutron log. For this reason the bed thickness should be picked from the gamma ray log and applied to the neutron log for determining the true radioactive values of thin beds.

On an out-hole gamma ray log the lower boundary of any lithologic break is indicated at the depth at which the detector actually enters the lithologic break and on the log is designated as the depth at which the pen actually begins to move from one level of radioactivity into another level of radioactivity. On leaving the above mentioned lithologic break, the top may be determined as the depth at which the detecting instrument leaves the bed, or the depth on the log at which the pen begins to travel to a new level of radioactivity. This is illustrated in Fig. 1.

In determining the equation for correcting the gamma ray deflection to true radioactivity level, the length factor of the detecting instrument may be neglected. The equation is plotted as Curve H in Fig. 6.

$$R_t/R_a = \frac{1}{1 - e^{-T/D}}$$

$R_t$ = true radioactivity level  $T$ = bed thickness
$R_a$ = apparent radioactivity level  $D$ = drag

The equation is plotted in Fig. 7.

In considering the neutron log, the spacing between the Scintillometer and the neutron source is taken as the length of the detecting system. This is possible because both the detector length and the source length are negligible as compared to the entire length of the system. The formula for determining the ratio of the true radioactivity level to the apparent level is as follows:

$$\frac{R_t}{R_a} = \frac{L/D}{\text{Log}_e \dfrac{e^{L/D} \times e^{T/D}}{e^{L/D} + e^{T/D} - 1}}$$

Fig. 6 shows curves plotted from the equation using $L/D$ factors of 0, .5, 1, and 2. In common logging prac-

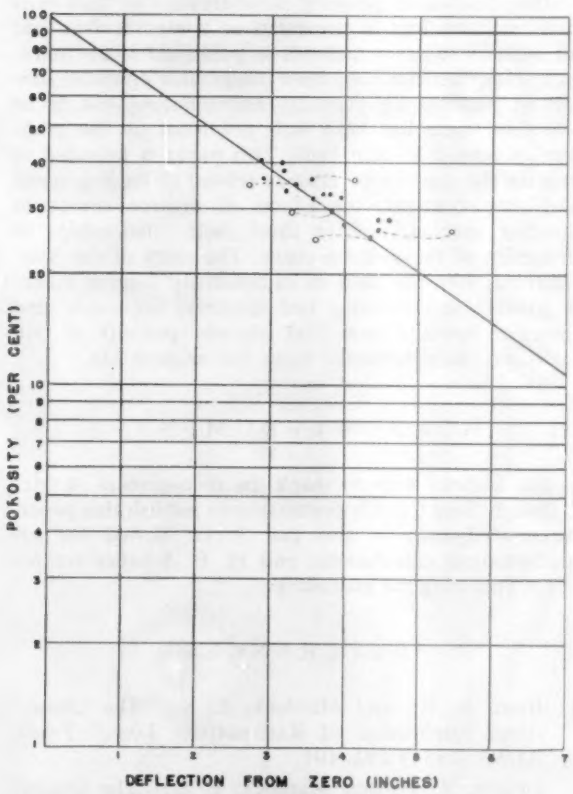


FIG. 4 — PLOTTED CORE POROSITY AND NEUTRON DEFLECTION. CIRCLES REPRESENT DEFLECTION OF THIN ZONES BEFORE CORRECTION FACTOR APPLIED. NOTE HOW CLOSE THE POINTS FALL TO THE POROSITY CURVE AFTER THE CORRECTION HAS BEEN MADE.

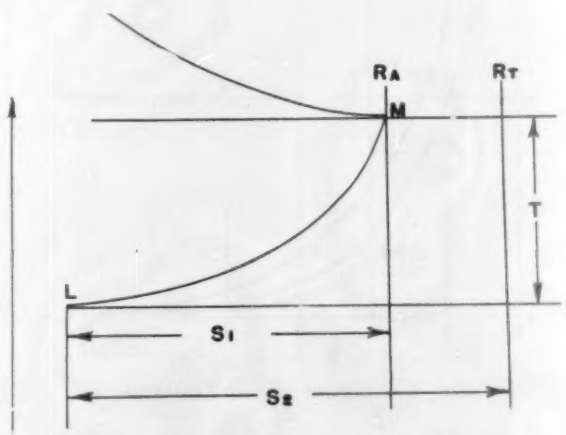


FIG. 5 — IDEALIZED RADIOACTIVE LOG CURVE.

As the scintillation counter reaches depth "L," the pen commences to move laterally to depth "M" as the counter moves to depth "M." $R_a$ is the line of apparent radiation as measured by the instrument. $R_t$ is the line of true radiation. Counter enters bed at depth "L" and leaves at point "M." "T" is the bed thickness. $S_1$ is the distance from "L" to $R_a$. $S_2$ is the distance from "L" to $R_t$.

tice the $L/D$ value will fall between the factors .5 and 1. Drag may be calculated from the time constant and logging speed as shown on the log heading. Source spacing should also be noted on the log heading.

The procedure for determining the true radioactivity level for thin beds on the neutron log is as follows: Where $R_t$ = true radioactivity; $R_a$ = apparent radioactivity; $T$ = bed thickness; $D$ = drag; and $L$ = length of the detecting system:

1. Determine $T$ from the gamma ray log.
2. Determine $D$ from the neutron log instrument settings.
3. Determine $L$ from the neutron log spacing.
4. Calculate $L/D$ and $T/D$.
5. Enter the appropriate curve on Fig. 6 and determine $R_t/R_a$.
6. Measure $R_a$ from the neutron log.
7. $R_t$ may then be solved by the equation

$$R_t = \frac{R_t}{R_a} \times R_a$$

If the $L/D$ factor falls between 0 and .5 or between .5 and 1, values can be interpolated from the curve in Fig. 6.

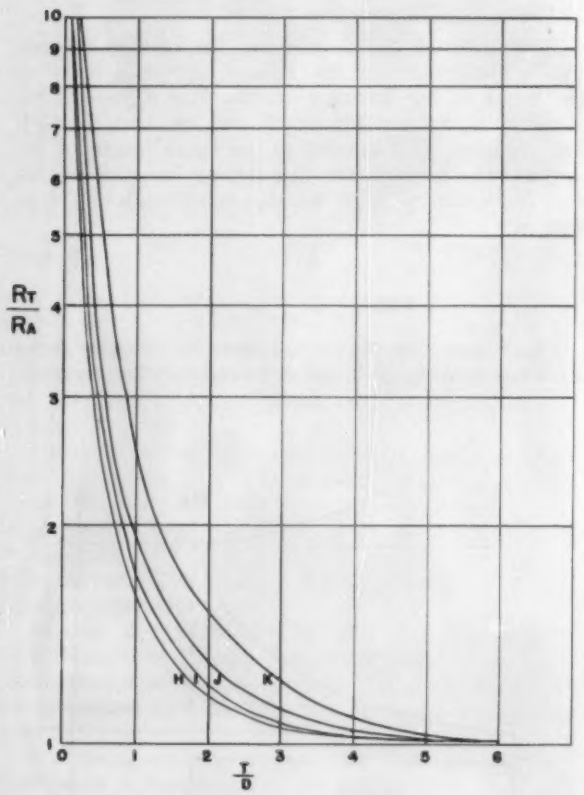


FIG. 6 — GRAPH OF THE EQUATION

$$\frac{R_t}{R_a} = \frac{\frac{L}{D}}{\text{Log}_e \dfrac{e^{\frac{L}{D}} \times e^{\frac{T}{D}}}{e^{\frac{L}{D}} + e^{\frac{T}{D}} - 1}}$$

Curve H: $L/D = 0$
Curve I: $L/D = .5$
Curve J: $L/D = 1$
Curve K: $L/D = 2$

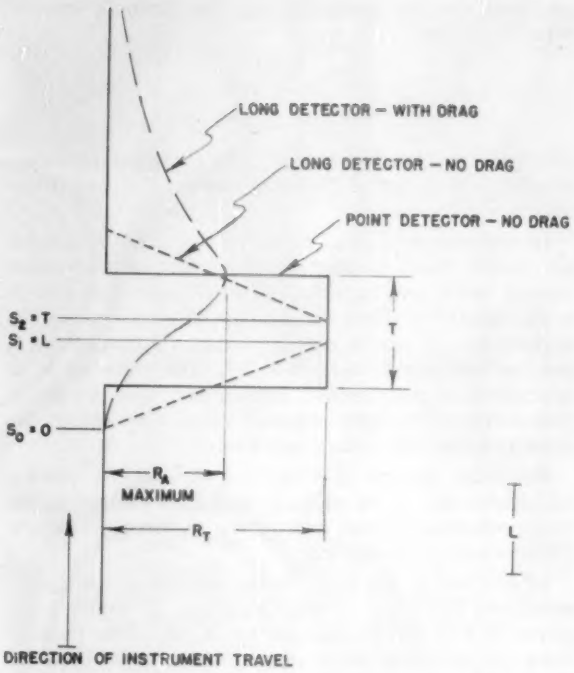


FIG. 7 — EFFECT OF LENGTH OF DETECTING SYSTEM.

## CONCLUSIONS

This method of porosity determination of thin beds from neutron logs is presented as a modification and an addition to other methods as published in the literature. Many articles have been contributed upon the subject of neutron log porosity determination, but up to this time there has been little published on the problem as related to thin beds. This paper is intended to explain the concept of drag as related to logging speed and time constant, the effects of neutron source to detector spacing, and to show their relationships to deflection of the neutron curve. The entry of the Scintillometer into the field of radioactivity logging makes it possible to determine bed thickness accurately and therefore opens a new field whereby porosity of thin beds may be determined from the neutron log.

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## APPENDIX

### DERIVATION OF THE EQUATION FOR DETERMINATION OF TRUE RADIOACTIVITY

The assumptions used in deriving the equation are as follows:

1. Borehole effect is neglected.
2. Adjacent bed effect is neglected.
3. The spacing between the Scintillometer and the neutron source is considered as the length of the detection system.
4. The detector is equally sensitive along its length.

The symbols used as as follows and the conditions illustrated in Fig. 7.

$R_t$ = true radioactivity level
$R_a$ = apparent radioactivity level
$T$ = bed thickness
$D$ = drag
$L$ = length of detecting system
$S$ = distance along the borehole

(1) The response $R(S)$ along the borehole to a single linear rise is:

$$R(S) = \frac{1}{L}(S - D[1 - e^{-S/D}])$$

(2) In the vicinity of $R_a$ (maximum) the total response is:

$$R = R(S) - R(S - L) - R(S - T)$$

$$= \frac{1}{L}(S - D[1 - e^{-S/D}])$$

$$- \frac{1}{L}(S - L - D[1 - e^{\frac{-(S-L)}{D}}])$$

$$- \frac{1}{L}(S - T - D[1 - e^{\frac{-(S-T)}{D}}])$$

$$= \frac{1}{L}(-S + D + L + T + De^{-S/D}[1 - e^{L/D} - e^{T/D}])$$

(3) To find $R$(maximum), let $\frac{dR}{dS} = 0$, and eliminate $S$.

$$\frac{dR}{dS} = \frac{1}{L}(-1 + D\left[-\frac{1}{D}\right]e^{-S/D}[1 - e^{L/D} - e^{T/D}]) = 0$$

since $e^{-S/D}(1 - e^{L/D} - e^{T/D}) = -1$

then $-S = D \operatorname{Log}_e \frac{1}{e^{L/D} + e^{T/D} - 1}$

$$R \text{ (maximum)} = \frac{1}{L}(D \operatorname{Log}_e \frac{1}{e^{L/D} + e^{T/D} - 1} + L + T)$$

$$= 1 + \frac{T}{L} + \frac{D}{L} \operatorname{Log}_e \frac{1}{e^{L/D} + e^{T/D} - 1}$$

$$= \frac{D}{L} \operatorname{Log}_e \frac{e^{L/D} \times e^{T/D}}{e^{L/D} + e^{T/D} - 1}$$

(4) $$\frac{R_t}{R_a} = \frac{1}{R \text{ (maximum)}}$$

(5) $$\frac{R_t}{R_a} = \frac{L/D}{\operatorname{Log}_e \frac{e^{L/D} \times e^{T/D}}{e^{L/D} + e^{T/D} - 1}}$$

(6) In order to determine $R_t/R_a$ for the gamma ray curve, neglect $L$.

$$\frac{R_t}{R_a} = \frac{1}{1 - e^{-T/D}}$$

***

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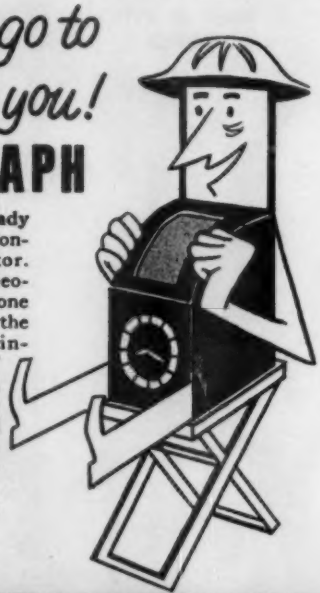

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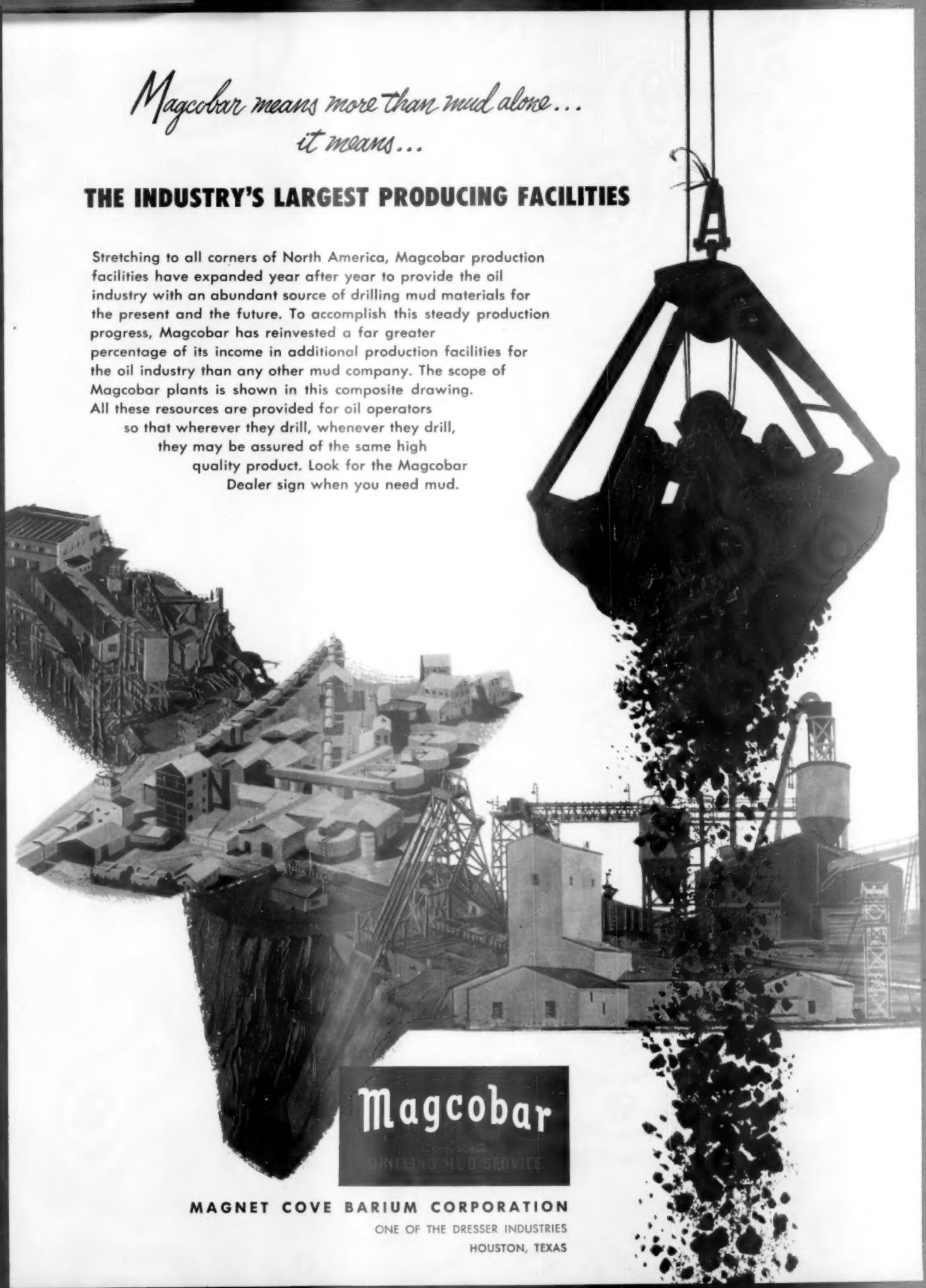


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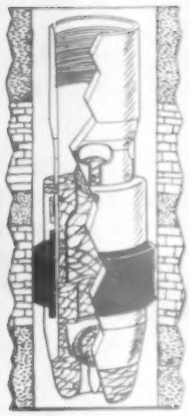

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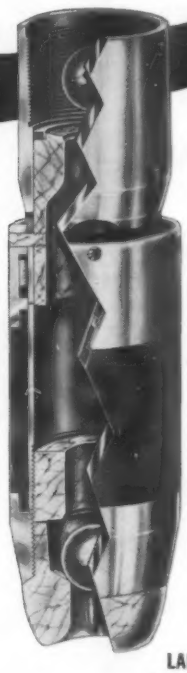

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